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Transition to a Low Carbon Energy System:
Looking ahead on regional needs for minerals and materials

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Dedicado à Natureza e a todos os que trabalham para a conservar.

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SUMÁRIO

A civilização global precisa de mudar. Os níveis de poluição atuais não são sustentáveis nem reversíveis, mas existe a possibilidade de abrandar os efeitos do aquecimento global. Dentro dos diferentes contribuidores para a poluição atmosférica global, aqueles ligados ao sector da energia (transportes e geração elétrica) representam uma fatia de aproximadamente 60% do total de emissões de Gases de Efeito de Estufa (GEE). Esta dissertação foca-se exatamente nestes dois subsectores e na sua transição para um sistema energético de baixo carbono. Utilizando 3 cenários da Agência Internacional da Energia (IEA), identificaram—se e quantificaram-se 31 materiais necessários (bauxite, boro, cádmio, cromo, cobalto, cobre, gálio, germânio, ouro, grafite, indium, ferro, chumbo, lítio, magnesite, manganês, molibdênio, níquel, nióbio, paládio, selênio, prata, tântalo, telúrio, estanho, titânio, tungstênio, vanádio, zinco, zircão e terras raras) essenciais para as tecnologias de baixo carbono considerados: energia eólica, energia solar, energia hidrelétrica, energia nuclear, energia geotérmica, energia do oceano, captura e armazenamento de carbono, mobilidade elétrica e baterias de armazenamento de eletricidade. A quantificação foi feita em escala global e separadamente para dez regiões do mundo (ASEAN, UE, China, EUA, Índia, Rússia, África do Sul, Brasil, México e África+), bem como para os grupos OCDE e não-OCDE, quanto às necessidades de materiais versus a sua extração nas respetivas regiões. Identificaram-se os materiais mais críticos de cada região e o risco em obter todos os materiais necessários de acordo com os cenários da IEA. Quantificou-se ainda o consumo de energia para a extração e concentração dos materiais totais. Concluiu-se que a média anual para o período de 2055-2060, para instalar entre [32 a 58,3 milhões] de veículos elétricos e [458,1 a 469,6 GW] de tecnologias de produção de eletricidade não fóssil, estimados pela IEA, corresponde a um total entre [19,585,988 e 25,430,698 t] de materiais o que representa um consumo anual médio entre [6 a 10,5 vezes] maior que o consumo anual médio para o período 2014-2025 para estas tecnologias, de acordo com o três cenários (RTS, 2DS e B2DS). As tecnologias solares tipo PV *thin-film* e os veículos elétricos são as que maiores problemas criam a nível global em termos de aviabilidade de materiais. *telúrio, gálio, indium* são os materiais mais críticos utilizados em PV *thin-film*, e lítio, cobalto, grafite e terras raras os mais críticos utilizados em veículos eléctricos. À escala regional, conclui-se que de entre as regiões estudadas, a Índia é a região mais dependente de materiais importados para a instalação de tecnologias de baixo carbono que permitam o crescimento em consumo de eletricidade expectável, posicionando-se assim como a região de maior risco teórico. Materiais como o cobre, níquel, molibdeno e chumbo necessitara provavelmente de aumentar significativamente a produção mundial e/ou as taxas de reciclagem. Nesta análise não se teve em conta o potencial de reciclagem, o potencial de substituição ou de eficiência no uso de materiais no futuro, pelo que as necessidades estimadas podem estar sobrestimadas.

Palavras-Chave: transição energética; materiais críticos; demanda regional; tecnologias de baixo carbono; ETP; IEA;

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ABSTRACT

Global civilization needs to change. Current pollution levels are not sustainable or reversible, but there is the possibility of slowing down the effects of global warming. Within the different contributors to global air pollution, those connected to the energy sector (transport and electricity generation) represent a slice of approximately 60% of the total emissions of Greenhouse Gases (GHG). This dissertation focuses on exactly these two subsectors and the required transition to a low-carbon energy system. This dissertation uses scenarios produced by the International Energy Agency (IEA) for the ETP 2017 and analyses potential bottleneck occurrences for 31 materials (bauxite, boron, cadmium, chromium, cobalt, copper, gallium, germanium, gold, graphite, indium, iron, lead, lithium, magnesite, manganese, molybdenum, nickel, niobium, palladium, selenium, silver, tantalum, tellurium, tin, titanium, tungsten, vanadium, zinc, zircon and rare earths elements) essential for the low carbon technologies considered: wind power, solar power, hydro power, nuclear energy, geothermal energy, ocean energy, carbon capture and storage, electric mobility and electricity storage batteries. The quantification was made at a global scale and separately for ten regions of the world (ASEAN, EU, China, USA, India, Russia, South Africa, Brazil, Mexico and Africa+) as well as for the OECD and non-OECD groups in terms of needs of materials versus their extraction in their respective regions. The materials most critical to each region and the risk of obtaining all the necessary materials were identified, according to IEA ETP'17 scenarios. The energy consumption for the extraction and concentration of the total materials is also estimated. It was concluded that the annual average for the period of 2055-2060, to install between [32 to 58.3 million] of electric vehicles and [458.1 to 469.6 GW] of non-fossil electricity production technologies, estimated by the IEA, corresponds to a total [19,585,988 and 25,430,698 t] of materials which represents an average annual consumption [6 to 10.5 times] higher than the average annual consumption for the 2014-2025 period for these technologies, according to the three scenarios (RTS, 2DS and B2DS). Solar PV Thin-Film technologies and electric vehicles create the biggest problems at the global level in terms of material availability. Tellurium, gallium, indium are the most critical materials used in thin-film PV and lithium, cobalt, graphite and rare earth the most critical used in electric vehicles. On a regional scale, it is concluded that among the regions studied, India is the region most dependent on materials import for the installation of low-carbon technologies that would allow expectable growth in electricity consumption, positioning itself as the region with the highest theoretical risk. Materials such as copper, nickel, molybdenum and lead would probably need to significantly increase global production and/or recycling rates. In this analysis the potential effect of recycling, the potential for substitution or efficiency in the use of materials was not considered which may overestimate the overall material requirements.

Keywords: energy transition; critical materials; regional demand; low carbon technologies; ETP; IEA;

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LIST OF ABBREVIATIONS AND ACRONYMS

2DS	2º Degree Scenario
ASEAN	Association of Southeast Asian Nations
B2DS	Beyond 2º Degree Scenario
BEV	Battery Electric Vehicles
CCS	Carbon Capture And Storage
CSP	Concentrated Solar Power
ETP	Energy Technology Perspectives
EV	Electric Vehicle
GDP	Gross Domestic Product
GHG	Greenhouse Gases
HEV	Hybrid Electric Vehicle
IEA	International Energy Agency
OECD	Organisation For Economic Co-Operation And Development
PHEV	Plug-In Hybrid Electric Vehicle
PV	Photovoltaics
RE	Rare Earth's
REE	Electrical and Electronic Waste
RES	Renewable Energy Sources
RTS	Reference Technology Scenario
T&D	Transmission & Distribuiton
USGS	United States Geological Survey

Ag	Silver	**In**	Indium	**Sn**	Tin
Al	Aluminium	**Li**	Lithium	**Ta**	Tantalum
B	Boron	**Mg**	Magnesium	**Tb**	Terbium
C	Graphite	**Mn**	Manganese	**Te**	Tellurium
Cd	Cadmium	**Mo**	Molybdenum	**Ti**	Titanium
Co	Cobalt	**Nb**	Niobium	**Va**	Vanadium
Cr	Chromium	**Nd**	Neodymium	**W**	Tungsten
Cu	Copper	**Ni**	Nickel	**Zn**	Zinc
Dy	Dysprosium	**Pb**	Lead	**Zr**	Zirconium
Fe	Iron	**Pr**	Praseodymium	**RE**	Rare Earths
Ga	Gallium	**Se**	Selenium		

1 INTRODUCTION

1.1 Framing and motivation

Climate change is one of the biggest global concerns of the XXI century. Since the beginning of the industrial age, emissions of greenhouse gases (GHG) have escalated to annual amounts never seen before, mostly due to the replacement of human work by machines that operate by burning fossil fuels either directly or indirectly by using electricity. The use of electricity became widespread in the late XIX and early XX centuries when it became firstly generated via the burning of coal, and later other fossil fuels as oil, natural gas and much more recently renewable energy sources (RES). The scientific community has long warned about the consequences of pollution on the environment and ecosystems, whether it is in solid, liquid or gaseous mode.

The speed at which Human beings exploit the world resources is a concern that comes from the late XIX century with the publication of the article “An Essay on The Principle of Population” by Thomas Malthus (Malthus 1798). Malthus concluded that the speed at which the population was growing was far superior than the speed of which we could produce food, with the first growing geometrically and the second arithmetically. This theory marked the beginning of an issue previously non-existent: the thought of limits of resources on the planet or of a minimum speed at which they could be restored.

The work by Malthus served as a base for the publication of the book entitled “The Limits to Growth” (1972) by the Club of Rome, a group of 30 people from the most diverse scientific areas. Using Mathematical models, this group anticipated that the current growth of the world economy, population and subsequent consumption of resources and ecological footprint, could not be sustained for longer than 2100. The Club then pointed out that the only solution is to take a quick and strong global policy so as not to worsen the future of the planet and of humans. The ideas in this book are strongly correlated with this dissertation. Not only is there a need to try and revert the level of existent pollution, with a transition to a low-carbon energy system, but also the need not to have shortages in the stock of resources, being them non-renewables, such as metals and minerals, or renewable as water and biomass. It is also essential to be aware of the impacts produced by exploration and extraction of resources (Nykvist et al. 2013).

Within this context a very urgent necessity is the world’s energy transition to a low-carbon system. This is worrying because not only does it need to happen, as it must happen in a relatively short period and at a global scale. The magnitude of the low-carbon technologies to be implemented and the probable extinction of traditional technologies based on fossil fuel makes this transition a huge challenge for the XXI century (Tollefson 2018)

In this context, the Paris agreement, ratified by 184 parties (UNFCCC 2018), has stated it is necessary to carry out a quick reduction of GHG so as not to exceed the rise of 2 º C of the global average temperature compared to the pre-industrial period. Approximately 2/3 of GHG emissions stem from the generation and use of energy, and the reduction of dependence on fossil fuels is therefore necessary. The global energy system needs a historical change, requiring a new energy mix based on low-carbon technologies (UNFCCC 2015). There is no time to lose and thus this transition will have to be economically viable, it should not present obstacles in the supply chains of the necessary resources and should not exacerbate environmental and social impacts (loss of biodiversity, poor human health) (de Koning et al. 2018)(Tollefson 2018)

Therefore, any obstacles to this transition, whether politico-economical or due to availability of resources, need to be identified, assessed and overcome. Another issue to be considered is that the problem of climate change is global and non-regional, and not always the most polluting areas will be the ones who suffer the greatest future consequences. The diversity of planetary region’s needs, and availability of human and natural resources need to be considered.

Another one of the problems for this transition is the needs for use of materials. Low-carbon energy technologies have a much higher requirement for materials than traditional energy technologies currently used, which are manly the burning of coal for production of electricity and oil for transportation of passengers and goods (Kleijn 2012).

Not only large quantities will be necessary, but also there is a very large diversity and complexity of the materials required, some of which are only produced as by-products and/ or produced in only a few regions of the planet (Leopoldina, Acatech, and Akademienunion 2018). A fourth existing problem is the competition between uses, since we live in an age also entitled the 4th Industrial Revolution, where small sized technology devices are a part of everyone’s daily life (Goosey 2012). These devices such as smartphones, computers, sound systems, televisions, household cleaning appliances, food preparation appliances, etc. often use the same raw materials as the low-carbon technologies. The relative short lifespan of these appliances, their reduced mass, the diversity of materials embedded and the great and growing number of consumers worldwide, create the current problem of waste electrical and electronic equipment (WEEE). The WEEE are a problem because not only it presents hazardous waste for the environment, as it also represents a problem for recycling and recovery of materials due to the lack of economic incentives to do so. Such a thing can only be reversed in case the economic value of the materials used increases or a more efficient method is found for collecting and recycling them (Goosey 2012).

Among all material needs for both low-carbon energy technologies and other technologies, it should be mentioned that some of them are considered “critical”. Critical materials are those that are essential for economic development, as well as those at risk of not being available in large enough reserves at both regional and global level. A material can be critical for one country or continent and not for another. If the risk is at a global scale it is necessary to predict situations of insufficiency to be able to find alternative paths either by substitution of the material, by better recovery trough recycling or by a more efficient use of it, all in a timely manner. If the insufficiency is only at regional level, there is a need for geopolitical stability that allows the exchange of materials between regions that produce and the ones that require them.

In global terms the world’s metal production has been doubling every 20-25 years since the beginning of the last century (Schodde 2013). The mining industry is currently responsible for a considerable high share of global emissions, as well as for huge environmental and social impacts. due to changes in soil use, waste production and the overwhelming energy use in the course of extraction and processing. In recent years the concentration of the nearest ores to the surface has been diminishing (Norgate and Haque 2010). This leads to higher energy consumption for the exploitation of viable deposits at greater depths and for processing minerals of lesser purity.

The energy transition comes to aggravate this situation due to the large amount of raw materials it requires. The International Energy Agency (IEA) has produced several publications which report and create hypothesis for possible future outcomes of the global energy system till 2050 and 2060. One of the most well-known of such documents is the Energy Technology Perspectives (ETP 2017), which presents three contrasting energy system scenarios up to 2060 for the planet as a whole and for its major geographic regions. The scenarios are named: Reference Technology Scenario (RST), 2-Degrees Scenario (2DS) and Beyond 2-Degrees Scenario (B2DS) and will be presented further in this dissertation.

1.2 Objectives and scope of the dissertation

With this dissertation it is intended to quantify the need of materials resources for the IEA’s three scenarios regarding main low-carbon technologies for electricity generation, energy storage and electric transport, for several major regions of the planet, as well as estimate energy consumption and emissions arising from the extraction of all the materials quantified and required for the transition to a low-carbon energy system. The analysis is done up to the year of 2060, according with the ETP 2017 scenarios.

The analysis was performed for the period 2014 till 2060 for the following geographical areas: BRICS (Brazil, Russia, India, China, South Africa), ASEAN, EU, USA, Mexico, Africa + as well as for the whole World, the OECD and the non-OECD countries.

The definition of materials considered in the dissertation are those used in each of the low carbon technologies considered. A total of 31 materials are studied, namely: Bauxite, Boron, Cadmium, Chromium, Cobalt, Copper, Gallium, Germanium, Gold, Graphite, Indium, Iron, Lead, Lithium, Magnesite, Manganese, Molybdenum, Nickel, Niobium, Palladium, Selenium, Silver, Tantalum, Tellurium, Tin, Titanium, Tungsten, Vanadium, Zinc, Zircon, Rare Earths

The following research questions were answered:

- Are there enough materials resources to ensure the deployment of the IEA's scenarios for a transition to a low carbon energy system?

- Which materials are more critical for this transition, globally and per region?

- Are there enough resources for the major regions of the planet?

- What is the expected growth of mining operations to meet each of the three IEA's scenarios needs?

-What could be the implication in terms of energy consumption associated with the extraction of the raw materials necessary for the transition to a low carbon system?

1.3 Structure of Dissertation

This dissertation starts by analysing the different existent scenarios for the energy transition to a low carbon energy system. This is followed by a review of different studies in the same theme, comparing methodologies, materials and boundaries considered. The objective of this dissertation is defined based on the identified knowledge gaps.

Section 3 describes the used methodology. It is structured in 4 sub sections: 1) materials use factors for the low-carbon technologies; 2) IEA low carbon scenarios and estimated material needs; 3) analysis of global mineral productions and reserves; 4) estimate of energy consumption from materials extraction.

The results are then presented in section 4 starting with an overview of the quantified use of materials' needs for low-carbon energy technologies till 2060, both at global and regional level. This is followed an assessment of potential materials' supply bottlenecks per region and per technology. An estimate of the energy consumption needs for the extraction of materials in the various regions is presented.

Section 5 concludes the dissertations and highlights the necessary future developments for a more thorough study, as well as the impacts that new emerging technologies can have on the analysis made in this dissertation.

2 LITERATURE REVIEW

In the next section a simple comparison is made between the scenarios of the ETP17 and others produced by private companies such as Equinor and public organizations like the World Energy Council. This comparison is important in order to evaluate the different options and dimensions for the energy transition, according to different perspectives.

This subject already has had several studies which based on scenarios try to estimate the necessary future decisions that make sure there is enough supply for the various economic activities, such as the studies presented on Table 1 which will be detailed further in this section, The literature review is concluded with an overview of the most relevant environmental impacts associated to mining activities.

2.1 Brief overview of low carbon energy scenarios

The creation of low carbon energy scenarios is of most importance due to the real need to make the energy transition to a low carbon energy system happen. Energy scenarios provide a framework for exploring different paths into the future, including various combinations of technology options and their implications (UNDP 2000). As energy systems are of large proportions, changes in it are slow and require long time horizons. Scenarios are neither predictions nor forecasts but simple options or paths of how the future might unfold and the consequences of different choices. Energy scenarios are a useful tool for industry experts, government officials, academic researchers and general public for their policy-making, planning and investment decisions (Paltsev 2016). Some scenarios describe the trajectories that are required to drive the energy system towards a specific objective such as a particular atmospheric CO2 level (IEA, 2015), while some other scenarios look at the current policy development to stress that the current trajectory leads to some undesirable outcomes that need to be corrected with future policies (Clarke et al. 2014) (Paltsev 2016). "In scientific energy assessments, scenarios are usually based on an internally consistent, reproducible set of assumptions or theories about the key relationships and driving forces of change, which are derived from our understanding of both history and the current situation" (UNDP 2000). Energy is essential for our current society in all its forms, but electricity is expected to play the major role in our future energy system.

Besides the already mentioned IEA ETP scenarios there are other scenarios, namely from the World Energy Council (WEC) and Equinor. "Formed in 1923, the Council is the UN-accredited global energy body, representing the entire energy spectrum, with over 3,000-member organisations in over 90 countries, drawn from governments, private and state corporations, academia, Non-Governmental Organisations (NGOs) and energy stakeholders." (WEC 2016)(WEC 2018). Other highly prominent scenarios come from Equinor (ex-Statoil) a Norwegian multinational energy company present in 36 countries, with 67% owned by the Norwegian state, that focuses mainly in fossil fuels (oil and natural gas), but it also has total or partial ownership of wind farms (290 MW in production)(Equinor 2018a). It was selected by Forbes magazine in 2018 as the 91st largest global oil and gas public company (Forbes 2018).

The report by Equinor "is published for the 8th consecutive year. It presents three scenarios; Reform, Renewal and Rivalry, that span a vast outcome space for all important characteristics of the global energy system, such as macroeconomic development, global energy demand, GHG emissions, energy mix and oil and gas markets towards 2050. The report shows how policy, technology and market conditions can move development in different directions, both desired and undesired" (Equinor 2018b). Reform build on recent and current trends within market and technology development, rather than policy support, to be the main driver of change. Renewal represents a future trajectory, supported by strong, coordinated policy intervention, that delivers energy-related emission reductions consistent with the 2°-target on global warming. Rivalry describes a volatile world, where development and policy focus are determined mainly by geopolitics and other political priorities than climate change." (Equinor 2018b)

The report by WEC presents three scenarios: "Modern Jazz, which represents a 'digitally disrupted,' innovative, and market-driven world. Unfinished Symphony, a world in which more 'intelligent' and sustainable economic growth models emerge as the world drives to a low carbon future, and a more fragmented scenario called Hard Rock, which explores the consequences of weaker and unsustainable economic growth with inward-looking policies. All three scenarios have then been quantified using a global, multi-regional energy system model." (WEC 2016)

The IEA presents very ambitious scenarios which estimate a growth in energy consumption, as well as in electricity sourced from renewable sources. The B2DS can be compared with the Unfinished Symphony scenario by(WEC 2016), which estimates that by 2060 a larger share of renewables in the electricity mix, but a total TWh generated of about 8,500 TWh lower than the IEA's most ambitious scenario (B2DS)(WEC 2016). The Equinor's best possible scenario regarding RES is called Renewal and has a 40% share of renewable energy and about 40,000 TWh of total electricity generation, by 2050 (Equinor 2018b)

Source	Time Frame	Scenarios	Share of low carbon technologies in the overall electricity mix	World generated electricity in TWh
IEA ETP 2017	2060	RTS	45%	53,429
		2DS	74%	50,662
		B2DS	78%	53,123
World Energy Council 2016	2060	Hard Rock	55%	44,914
		Modern Jazz	60%	48,491
		Unfinished Symphony	81%	44,474
Equinor Energy Perspectives 2018	2050	Rivalry	23%	38,000*
		Reform	30%	45,000*
		Renewal	50%	40,000*

***aproximated values**

The two scenarios compared with the ETP originate in very different organizations, with different views of future energy pathways. Both have into account some type of data per regions of the world, as well as data on electric vehicles sales, which makes them comparable to the scenarios used in terms of technologies covered. It was the objective of this short section to compare different energy scenario sources with source of the scenarios used. The are other energy scenarios which are not here presented and there is also more information than the one here presented. A deeper comparision should be done but it was out of this dissertation objectives and it is left as future developments.

2.2 Studies that assess material needs for low-carbon energy technologies

There are several studies that try to estimate and analyse the risks associated with the transition to a low-carbon energy system. Some focus on the global level such as (Roelich et al. 2014)**,** (Öhrlund Isak 2012)**,** (Elshkaki and Graedel 2013)**,** (WWF 2014)**,** (Grandell et al. 2016)**,** (World Bank Group and EGPS 2017)**,** (de Koning et al. 2018)) that will be further described in this section**,** while others focus their analysis at a regional level. This is case of the word on the following authors for the EU: **(**(Moss et al. 2011, 2013)**,** (Blagoeva, Alves Dias, *et al.*, 2016)). In this EU-wide analysis the authors consider as critical materials those which have a higher consumption than the production and/or reserves and a great importance for the energy transition. The next table summarizes the most relevant studies assessing materials needs for low-carbon-energy technology deployment.

Table 1 - Studies that assess the material needs for low-carbon technologies

	Authors	End-year for the analysis	Spatial scope	Low-carbon energy technologies	Materials	Considered Most Critical by the authors
I	(Moss et al. 2011)	**2030**	**EUROPE**	NUC, SPV, WO & WOF, CCS, BIO, T&D	Te, In, Sn, Hf, Ag, Dy, Ga, Nd, Cd, Ni, Mo, V, Nb, Cu, Se Pb, Mn, Co, Cr, W, Yt, Zr, Te	Dy, Nd, Te, Ga, In
II	(Dawkins et al. 2012)	**2035**	**GLOBAL**	SPV WO & WOF EV & HEV	Li, Co, Nd, In, Te	In, Te
III	(Öhrlund I. 2012)	**2030**	**GLOBAL**	SPV, WO & WOF	Al, Ag, B, Cd, Co, Cr, Cu, Ga, In, Pb, Se, Si, Sn, Te, Dy, Fe, Mn, Mo, Nb, Nd, Ni, Pr, Sm, Tb, Zn	Ga, In, Se, Te, Dy, Nd, Pr, Tb
IV	(Elshkaki and Graedel 2013)	**2050**	**GLOBAL**	NUC, BIO, GEO, HYDRO, CSP, SPV, WO & WOF	Ag, Al, Cd, Cr, Cu, Fe, Ga, Ge, In Mo, Ni, Pb, If, Te, Zn, Nd, Dy, Mg Mn	Ag, Te, In, Ge
V	(Moss et al. 2013)	**2030**	**EUROPE**	HYDRO, GEO, OE, EV, FC, ES, EL	Li, C, Nd, Pr, Te, In, Sn, Pt Tb, I, Yt, Ge, Ga	Dy, Nd, Te, Ga, In, Eu, Tb, Y, Pr, C, Ge, Pt, Re, Hf
VI	(WWF 2014)	**2050**	**GLOBAL**	SPV WO & WOF EV, EL, T&D	In, Ga, Te, Y, Nd, Ag, Li, Co	In, Ga, Te, Li, Co
VII	(Blagoeva et al. 2016)	**2030**	**EUROPE**	SPV WO & WOF EV & HEV	Nd, Pr, Dy, Te Ag, In, Ga, if, Cu, Cd, Te, Li, Co, C	Dy, Eu, Tb, Y, Pr, Nd, Ga, Te
VIII	(Grandell et al. 2016)	**2050**	**GLOBAL**	PV, CSP WO & WOF EV, ES, EL, FC	Ag, Nd, Pr, Dy, Tb, Yt, La, Ce, EU, Co, Pt, Ru, In, Te	Ag, Te, In, Dy, La, Co, Pt, Ru
IX	(World Bank Group and EGPS 2017)	**2050**	**GLOBAL**	WO & WOF, SPV, ES	Al, Fe, Mo, Cr, Li, Ag, Cu, Pb, In, Mn, Zn	Not available
X	(de Koning et al. 2018)	**2050**	**GLOBAL**	SPV, WO & WOF NUC, EV	Al, Cu, Cr, Dy, Fe, In, Li, Nd, Ni, Pb, Zn	Any unlikely to be a bottleneck

Note: SPV - Solar Photovoltaics; CSP – Concentrated Solar Power; WO – Wind Onshore; WOF – Wind Offshore; Hydro – Hydropower; GEO – Geothermal ; OE – Ocean Energy; CCS – Carbon Capture and Storage; NUC – Nuclear; EV – Electric Vehicles; FC – Fuel Cells; ES – Energy Storage; EL - Efficient Lighting

For quite some time, it has been investigated the issue of availability of raw materials to meet the needs of the world and/or its regions. An example is the study carried out in 1975 funded by the Department of Defence of the United States of America (Curtis M. Jackson and Dunleavy 1975). The study assessed the need of materials for 57 existing and emerging technologies at the time, eventually selecting six for further research. Of the selected technologies the authors concluded that two technologies presented problems due to the materials used: 1) Fuel Cells, because of the need for Platinum Group Metals (PGM) and 2) Superconductors, because of the need for helium, niobium, copper, nickel and chromium. (Curtis M. Jackson and Dunleavy 1975)

Critical raw materials (CRMs) are defined by the US Geological Survey as "Mineral commodities that have important uses and no viable substitutes, yet face potential disruption in supply" (USGS, 2017). The

European Commission, which has released the first list of CRMs in 2011, defines it in a similar way as "raw materials of high importance to the economy of the EU and whose supply is associated with high risk" without specifying if they are to be used in technology (European Commission 2010). With these two definitions it can be concluded that the main features that define a material as critical are supply risk and economic importance for the region and its industries.

After the adoption of the Raw Materials Initiative by the European Commission in 2008, the Joint Research Centre (JRC) published a report on the availability of raw materials for the energy transition to low-carbon technologies as portrayed by the EU SET plan (Strategic Energy Technology Plan). In this plan and report six energy technologies were considered: nuclear, solar PV and CSP, wind, bioenergy, CCS, transmission and distribution lines (European Commission 2015) (Moss et al. 2011). The objectives of the EU and of the SET plan are to reach 3 targets until 2020: 1) 20% reduction of CO_2 emissions in relation to 1990, 2) 20% of gross of energy consumption from RES and 3) 20% reduction in primary energy consumption through energy efficiency measures. With the most ambitious scenario in mind, the authors selected materials that would require at least 1% of world production, which narrowed the initial list of 60 materials to 14.

To evaluate the criticality of each material the authors applied four criteria:

- Likelihood of a rapid increase in worldwide demand;
- Limitations on the increase in annual production, within a short temporal space;
- Supply risk on the exporting countries;
- The reserves available in the exporting regions;

Based on these four criteria the materials were categorized has having high, medium or low criticality.
The study went on with the release of two other reports by the JRC. In the second report, released in 2013, the authors of the first added three electricity generation technologies to the previous six analysed in 2011 (Hydropower, Geothermal and Ocean energy), as well as other non-energy producing technologies, but also essential for the transition to a low carbon energy system (Fuel cells and Hydrogen, Electricity storage, Electric vehicles, Desalinization). This new report had into account not only the SET plan, but also the EU Energy Roadmap 2050, with the long-term goal of reducing greenhouse gas emissions by 80-95%, when compared to 1990 levels (European Commission 2012). Considering the new additional technologies in the 2013 report and a review of the six from the first report, the list of CRMs broadened from 5 to 14 materials considered of high criticality.

In 2016, the JRC published a new study, this time with a greater focus on wind energy, solar PV and on electric vehicles. In this study it was used a new methodology which relied on sets of indicators aggregated in two dimensions, upstream and downstream. This way it has in consideration multiple factors that may come into play in the future such as: mineral resources availability, current and potential mining/refining suppliers, EU reliance on imports, macroeconomic, environmental and geopolitical factors, recycling and substitution. The JRC three reports also have into account key mitigation aspects such as increasing the regional production, recycling and potential substitution of materials (Darina T. Blagoeva et al. 2016)

With a focus on the global level, there has been an increased attention in recent years regarding the availability of CRMs for the low carbon energy technologies of the necessary energy transition. The World-Wide Fund for Nature (WWF) in partnership with consultancy company Ecofys released a report in 2014 regarding the issue of potential bottlenecks for the low-carbon energy technologies (WWF 2014). For this study, two scenarios were used, "The Energy Report" (TER) created by Ecofys and WWF and "New Policy scenario" (NPS) from the IEA. The TER estimates a global energy system based 95% on renewable energy and excludes CCS and nuclear energy by 2050. The IEA scenario is a business as usual (BAU) scenario that runs until 2035. From the comparison of these two scenarios, the WWF and Ecofys concluded that "many of the material bottlenecks for the TER scenario are not relevant for the NPS" and that "many of the material bottlenecks for the NPS are also not relevant for the TER scenario." This is due to the differences in technologies of the two scenarios. The TER, an almost 100% renewable scenario, anticipates very high quantities of solar and wind energy and a wide spread of electric vehicles, which creates bottlenecks for

Indium, Gallium, Tellurium, Lithium and Cobalt. On the other hand, the NPS envisions an energy system still very dependent of fossil fuels and thus not as demanding of these materials.

Another work regarding the effect of material scarcity on low carbon energy technologies was developed by the Stockholm Environment Institute in partnership with the business leader's initiative 3C (Combat Climate Change) (Dawkins et al. 2012). This study focused on wind and solar energy and on electric vehicles, following the IEA scenarios presented in the World Energy Outlook 2010 document and the World Economic Forum (WEF) scenarios presented in the Mining and Minerals Scenarios 2010. The authors identified five metals that they considered to be the most crucial to these technologies: cobalt, lithium, neodymium, indium and tellurium, and did a more in-depth analysis. In order to assess the criticality of each material, the research team used a calculator created by SEI which considered factors such as: demand of virgin ore, recycling, other demand, sub-technology mix and material use efficiency and the growth or changes in all this until 2035. It was concluded that of the five materials analysed, indium and tellurium presented a high risk of medium- and long-term supply shortage, while neodymium presented a medium risk in the medium term and a high risk in the long term. For lithium and cobalt, the results shown a limited risk of supply in the long term. With these results the group concluded that the solar technologies Cd-Te (Cadmium telluride) and CIGs (copper indium gallium selenide solar cell) are the ones which present the greatest risk. (Dawkins et al. 2012)

The study by STOA (Öhrlund Isak 2012) focuses only on wind and solar energy and concluded that eight of the elements (gallium, indium, selenium, tellurium, dysprosium, neodymium, praseodymium and terbium) may have its demand increase greatly due to the large deployment of photovoltaic cells and permanent magnet turbines. Other meaningful conclusions by the author were that there is a small capability of substitution of any of the eight materials, but a possibility of using other sub-technologies that do not require these materials. The author also calls to the attention of its readers that the recycling rate, at the time of the study, was less than 1%.

The work by (Elshkaki and Graedel 2013) also researched the materials required for electricity generation technologies at a global scale including, not only renewable energy technologies, but also the fossil fuel based technologies, such as coal , gas and oil. The study develops an estimate from 1980 until 2050 and has into account the efficiency of the technologies, their performance ratio, utilization rate, materials content, production capacity from primary and secondary sources and the possibility of substitution, as well as the inclusion of policy measures and of impacts of transitioning from fossil fuel technologies to low carbon technologies. This was possible due to the use of a multi-level dynamic material flow and stock model. It is also stated that the analysis is carried out on country and regional levels, but this data is not presented. The two authors concluded mainly that for all the metals needed for wind power there is no risk of supply bottlenecks constraining its long-term development. For the PV solar technologies, it was found out that silver, tellurium, indium and germanium create risks for the installation of the diverse thin film technologies that need each of these. The base metals (aluminium, copper, chromium, lead and iron) will present no pressure for the energy transition under the two scenarios used by the authors, with the exception of nickel, which requires an increase in production, although its demand in the short term can be fully met by secondary resources.

Using the TIMES model generator and the scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, the study by (Grandell et al. 2016) analyses the need for special metals for the installation of solar, wind, electricity storage, electrolysis, hydrogen storage, fuel cells, electric vehicles and energy efficient lighting until 2050 at a global scale. After analysing the global demand for fourteen materials (eight rare earth materials plus cobalt, platinum, ruthenium, indium and tellurium) this study concluded that silver used in solar photovoltaics and concentrated solar power is the main material at risk, since the model returned a demand for this material which is approximately 450% of total known reserves. Other materials at risk include tellurium, indium, dysprosium, lanthanum, cobalt, platinum and ruthenium. According to the authors some of these materials are not at risk of supply bottlenecks, even though all show consumption amounts larger than the estimated reserves and resources, since there is a large proportion that could come from secondary production already in place today. This is the case for platinum. With this analysis, the authors concluded that the scenario considered is not attainable, at least with the current known technologies and metal resources.

One of the most recent reports regarding the issue of critical materials for low-carbon technologies was produced and released by the World Bank in 2017 (World Bank Group and EGPS 2017). Using three scenarios by the IEA ETP 2015 (2DS, 4DS and 6DS) the authors made projections for materials demand up to 2050. The report analyses aluminium, nickel, cobalt, copper, iron ore, lead, lithium, manganese, rare earth metals, cadmium, molybdenum, indium, silver, titanium and zinc with a special focus on wind, solar and energy storage batteries (including electric vehicles). It has a special aim to understand the implications the energy transition will have on resource-rich developing countries and does this by mapping the production and reserves of the above metals. It concluded that countries in South America are in an excellent position to supply other countries in terms of copper, iron ore, silver, lithium, aluminium, nickel, manganese, and zinc. Africa also has a good position regarding platinum, manganese, bauxite, cobalt and chromium, but the region that has the best position is Asia and specially China, with large reserves and production of the much-needed rare earth metals as well as all other, thus being able to compete with whole continents in terms of production.

The report is cautious in providing actual conclusions by saying that it is hard enough to make a prediction on the sub-technologies (or intra-technologies) that are going to be dominant or the market share that they will occupy, and that each of these sub-technologies has a different speciality metal attached. It goes as far as using the example of lithium showing that the market share of the Li-ion technology has a major impact on the overall demand. For example, variation in between Li-ion technology market share representing 30% of vehicles batteries, 40% of grid-scale storage and 33% of decentralised energy storage or representing 50% of each market creates a difference in world demand of about 20 million tonnes of lithium.

The most recent study reviewed in this dissertation comes from (de Koning et al. 2018) and considers all the available electricity producing technologies electric mobility according with 4 scenarios. This is one of the few studies which assesses, not only speciality materials, but also some of the so-called base materials (Al, Cu, Ni, Pb, Zn)). The materials analysed were aluminium, copper, nickel, chromium, indium, neodymium, dysprosium, lithium, zinc and lead, at a global scale. In this study the authors also investigate, besides the annual demand and supply for these materials, the historical growth rates of supply and known reserves. This is an approach that is useful, but may also be deceiving, as what happened in the past does not necessarily repeats itself in the future, particularly regarding non-renewable resources such as minerals. The study does not consider recycling of materials as a supply option which might make the total demand an overestimation. The conclusions that were made are that the demand required up to 2050 can be met through the historical growth rates of supply and reserves. Still, the demand for these eleven materials should grow by a factor of 3 – 4.5 compared with the year 2000. Other aspects that are called to attention are that while no bottlenecks are likely to happen for these eleven materials, the transition is an uncertain one which causes big investments on new mines of a high-risk character. Also, the time it takes to open new mines (average of 10 years), the lower ore grades and concerns about environmental impacts of mining might create obstacles not foreseen that could constrain material supply.

Independently of the source of the scenarios used in each of these studies, all agree that the main low-carbon energy technologies for this transition will be wind and solar energy. These two sources of energy are readily available, well studied and in constant improvement. But since they will be the backbone of this transition, and due to being variable intermittent electricity producers, it will be needed high amounts of installed capacity. This presents a problem as they are more metal intensive than current fossil fuel-based electricity plants and thus more materials will be needed.

It is very difficult to envision of how the electricity mix of a future low carbon energy system might look like, as there is a high uncertainty on the sub-technologies that are to be used as well as on new ones that might appear in the next thirty to forty years. The most uncertain technologies are thin-film solar panels

(CdTe, CIGs and a-Si) and the use of rare earths in permanent magnets of electric vehicles and wind turbines. There is also some uncertainty on the future batteries features either for stationary electricity storage or for electric vehicles. Although lithium-ion batteries show the best current efficiency and life time, they are very energy- intensive to produce and difficult to recycle.

From all the studies reviewed it is understandable that the objective of this dissertation has not still been accomplished. That is, the objective of quantifying the required materials for the energy transition to a low carbon energy system per region of the world. This regional analysis helps to better assess the regions which present less supply risks and the regions which lack production of essential materials and are dependent on imports. Another gap observed in the current literature has to do with the environmental impacts and energy consumption required for the extraction of materials.

2.3 Overview of environmental impacts of the mining industry

The mining industry is responsible for a large number of environmental impacts and is a high consumption energy (mainly diesel and electricity) and water linked to the various activities of commencing and operating a mine (ELAW 2010). Figure 1 resumes the main stages common to all mines but excludes the operations of processing the material into a finished product.

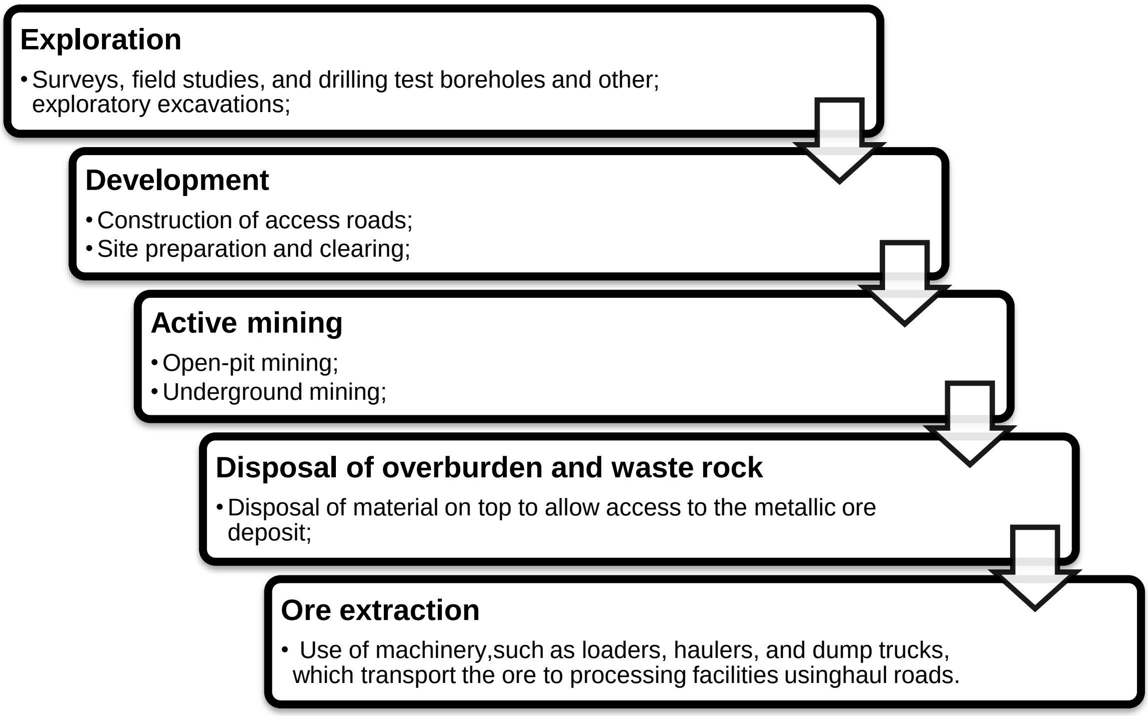


Figure 1 - Stages of a mining project; Source: (ELAW 2010)

During stage I, a geologist selects a site with the most potential of having large size mineral deposits. During this exploratory phase deep, shallow holes (boreholes) are excavated by large machines which sometimes require the clearing of wide areas of vegetation in order pass through. These sites may not prove worthy of moving into the next phase in case the ore deposit is not big enough or if it is of a low ore grade. Once a high value site is found, the engineers start planning the mine development. This entails the planning of wide access roads or rail networks for machinery and transport of ore or finished product. There is also the need to plan other infrastructures, such as houses for the workers, processing plant, waste rock and tailings storage, water treatment plants etc. At this time, it is necessary to decide if the mine will develop on the surface or underground. In case the mine develops as an open-pit (surface) mine it's necessary to remove vast amounts of rock which lays on top of the deposit (overburden/waste rock), as well as all the existent vegetation. As the open pit mine gets deeper it may sometimes hit groundwater tables or aquifers which requires that the water will be needed to be constantly pumped out of the mine, increasing energy the mine consumption. All the previous factors make this type of mining the most environmental destructive type. For an underground type not as much of waste rock needs to be removed as the access to the ore deposit is made through tunnels. This type of mine is much less environmental invasive, but a lot costlier, energy intensive and involves higher risks for workers such as risks of collapsing or quality of air inside the mine. After the mine has been built the ore extraction may commence and with it different environmental and social impacts, regardless to the type of mine being explored. A factor of great importance is the rehabilitation of the area and a return to its natural form. The problem is the mines operate for many decades and habitat restauration is very difficult, slow and costly process which gives no economic incentive to the prospectors of the closing mine.

Impacts on water

- Tailings leaching can contaminate surface and underground water bodys;

Impacts on air

- Particles emissions, direct GHG emissions from machinery;

Impacts on wildlife

- Habitat destruction and desflorestation, noise and human movement;

Impacts on soil

- Explosions, contamination by toxic materials, high land use and change;

Social impacts

- Poor work conditions;
- Health issues and hazard dutties;

Figure 2 - Most common impacts of mines construction and operation. Based on (ELAW 2010).

Large-scale mining projects have the potential to alter the global carbon budget in at least the following ways: (1) Lost CO_2 uptake by forests and vegetation that is cleared in order for mining to begin; (2) CO_2 emitted by machines consuming fossil fuels that are involved in extracting and transporting ore (e.g., diesel-powered heavy vehicles); and (3) CO_2 emitted by the processing of ore into metal (e.g., by pyro-metallurgical versus hydro-metallurgical techniques). (ELAW 2010)

All operations of a mine create serious impacts in the surrounding areas and atmosphere. Mining is the backbone of our civilization and is not disappearing as an economic activity because some materials are not recycled, as for example lithium, and because of the increasing population (Kleijn 2012). When impacts cannot be avoided there is the need to mitigate them, regardless of them being of social, economic or environmental type. In a mine this is a true challenge but not impossible - it requires a complete assessment of future operations and impacts in order to plan ahead the actions required to reduce them. There is also the need to improve efficiency of energy consumption by improving machinery efficiency, to reduce the use of fossil fuels and instead use electricity from renewable sources (Norgate and Haque 2010)

The energy transition will most probably require a large share of the global materials annually mined which will potentially increase the overall production.

3 METHODOLOGY

The entire analysis was carried out on the basis of the IEA ETP 2017 scenarios. In order to evaluate the possibility of material supply bottlenecks, different variables had to come into play. The estimated installed capacity of electricity generation technologies, number of hybrid and electric vehicles and electricity storage capacity according to the three scenarios were retrieved from ETP data for the different regions, with some assumptions when necessary. The materials use factors were gathered based on similar studies and life cycle assessments of specific technologies. Annual production of each material was collected for the year 2016 and retrieved from the annual publication (WMD, 2016) published by the Federal Ministry of Sustainability and Tourism of Austria. With all the previous information it was possible to assess the materials which present a higher risk of supply for each region and the materials which currently do not present the necessary production level to satisfy the demand by energy transition to a low carbon energy system according to each scenario.

3.1 Methodological approach

The following steps were followed:

I. The new installed capacity was obtained for the different scenarios and for the time intervals 2014-2025, 2025-2030, 2030-2035, 2035-2040, 2045-2050, 2050-2055 and 2055-2060. It has been assumed that growth within each interval remains constant over time. It was also assumed that the end of life and replacement of the different technologies are already considered on IEA ETP scenarios. An average value of new capacity annually installed (GW/year) was attained by dividing the value for the interval by the number of years that composes it. The same process was held for each region of the ETP and for each low-carbon technology. For the stock of electric vehicles (EV's) and battery storage capacity there was only data for the whole world in ETP 2017. In order to have a more complete quantification, it was necessary to distribute the data available across the considered regions. The stock of vehicles was thus distributed according to the share of total electricity consumption in transports stated for each region. The battery's capacity was allocated according with the share of variable renewables (wind and solar) per region.

II. Based on the available literature, particularly similar studies and life-cycle analyses of specific technologies, material use factors associated to low-carbon technologies were obtained *(tonne of material / GW capacity installed).* When several values from different sources were found, it was chosen to use the average of all.

III. The data of the annual production of the materials quantified in this study were retrieved from the annual publication (WMD, 2016) published by the Federal Ministry of Sustainability and Tourism of Austria in cooperation with the International Organizing Committee for the World Mining Congresses (publicly available at http://www.world-mining-data.info). This source has been chosen among other available because: 1) it is possible to download a spreadsheet with all the necessary mineral commodities in different tabs; 2) it shows all values for 2016; 3) it shows information for all the producing countries; 4) all data is for mineral content. The exception to the use of this source occurred with Indium and Cement, as no values were available. In the case of Indium, the data came from the British Geological Survey (BGS, 2016) annual publication, and in the case of Cement from the United States Geological Survey (USGS, 2016) because BGS only has values for European countries. BGS and WMD follow a similar methodology and show the production for all countries, which does not happen with USGS, that only shows the top producers and aggregates the remaining as “rest of the world”.

IV. To analyse the potential of supply bottlenecks across the different mineral commodities, it was necessary to obtain values of the world and regional mineral reserves. For this the only data available in the world is from USGS, and so it was the one used. Some inconsistencies in the data were found as sometimes there was only data for the reserves of a few countries and none for others that also produce the same minerals.

V. The data of the annual new installed capacity was multiplied by the materials use factors in order to estimate the total amount of materials required annually.

VI. The total amount of materials was then divided by the annual production of mineral commodities of each region and conclusions were taken.

VII. The theoretically energy consumption associated to the extraction of the estimated material needs was calculated for the ETP 2017 three scenarios by crossing data from two sources: one for the ore grades and the other an LCA of 3 mines, both further presented in the next sections.

VIII. An overall evaluation (ranking) was made on the basis of data from the different sources mainly IEA and WMD 2016. The author developed a set of seven indicators to compare the different studied regions regarding risk for bottleneck occurrences and materials imports.

IX. The indicators are:

i. **Nº of materials NP** – The number of materials not produced in the region, out of the 31 considered;
ii. **Nº of materials > 100% -** Number of materials for which the estimated amount required is equal or superior to all the production in 2016;
iii. **Nº materials > 500% -** Number of materials for which the estimated amount required is equal or superior to five times the production in 2016;
iv. **Nº Reserves >100% -** Materials which require more virgin material than the regional estimated reserves;
v. **Growth installed capacity** – Amount of new electricity capacity added to the region;
vi. **Growth electricity demand** – Amount of electricity produced/consumed in the region;
vii. **Average global demand of each material** – Estimated share of the total amount of materials quantified of each region;

Each indicator has the value of 1 to 3 and the results presented are the average of the values obtained by each region in each indicator.in each of the three scenarios. Based on the sum of the grades (1-3) of each category, the different regions were ranked from 1-10 with the higher level representing a higher risk for bottleneck occurrences and materials imports.
In Figure 3 the main steps of the methodology used are presented in a simplified way.

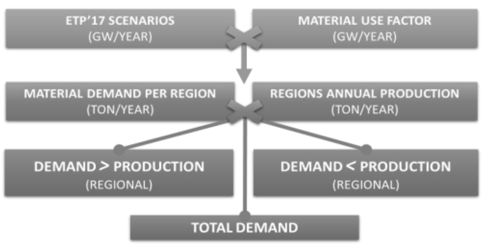


Figure 3 - Methodological approach used

3.2 IEA low carbon scenarios and considered material use factors

In this section the data available from the ETP 2017 is presented. First it will be shown the state of the world and of two major regions (OECD, non-OECD) for the year 2014, and the changes forecast by the ETP until 2060 in the three considered different scenarios (RTS, 2DS, B2DS). The regions considered in ETP can be visualized in Figure 4 and are presented in Table 2. For each region the data available in ETP will also be presented for 2014 and in the year 2060 according with the three scenarios.

The three IEA scenarios are described as follows:

"The **Reference Technology Scenario** (RTS) considers today's commitments by countries to limit emissions and improve energy efficiency, including the NDCs[1] pledged under the Paris Agreement. "
"The **2°C Scenario** (2DS) lays out an energy system pathway and a CO_2 emissions trajectory consistent with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100. "

"The **Beyond 2°C Scenario** (B2DS) explores how far deployment of technologies that are already available or in the innovation pipeline could take us beyond the 2DS. Technology improvements and deployment are pushed to their maximum practicable limits across the energy system to achieve net-zero emissions by 2060 and to stay net zero or below thereafter, without requiring unforeseen technology breakthroughs or limiting economic growth."

These three scenarios represent three levels of ambition in a transition to a low carbon energy system. According to the IEA only the B2DS has enough ambition to limit the rise of the average global temperature to below 2ºC above pre-industrial levels by the end of the century. The Paris agreement did not specify a target temperature but left it at "well below 2ºC" which only the B2DS presents a possibility of achieving with a 50% chance of limiting average future temperature increases to 1.75°C by 2100.

The 2DS, ETP's central climate mitigation scenario, is already highly ambitious in the changes it estimates and is designed to reduce today's annual energy-related CO_2 emission by 70% until 2060. According to the IEA even with this major effort there is only a 50% chance of achieving an increase of just 2ºC by 2100.

The RTS fails complying with the Paris agreement goals, but shows the current trajectory including the efforts already being made by the 195 nations that signed it. The changes estimated by this scenario would make the global average temperature to rise to 2,7ºC by 2100 and would continue to rise after, according with IEA. The map in Figure 4 shows the regions the ETP 2017 covers.

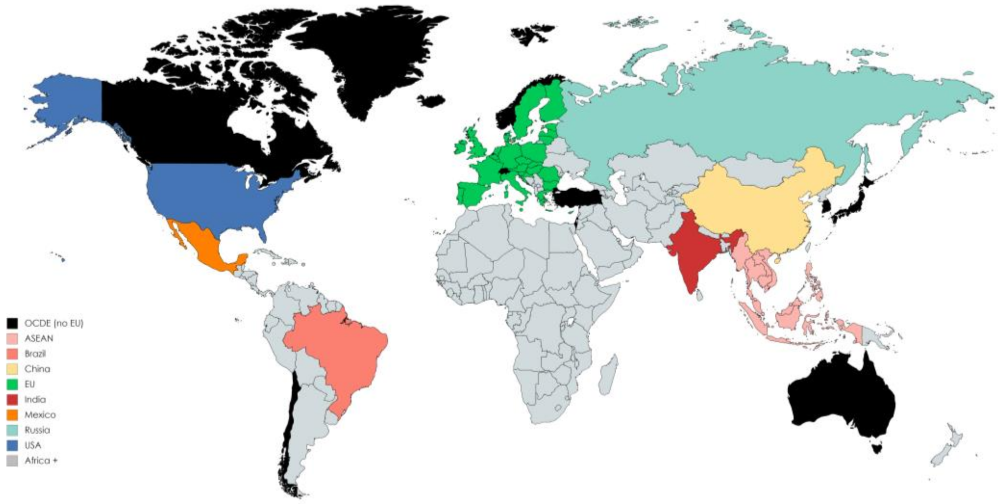


Figure 4 - ETP regions (in grey are the countries which constitute "Africa+")

[1] Nationally Determined Contributions.

In Table 2 is the list of countries that constitute the OECD, European Union, ASEAN and the group of countries created in this study (AFRICA+) in order to get an approximate value for the African continent, which was not entirely possible to isolate.

Table 2 - Group of countries of the regions considered in ETP and the group of countries that constitute Africa + group. In bold are the countries for which there is individual data.

OECD Countries			European Union		ASEAN	Africa +
Australia	Ireland	Slovenia	Austria	Italy	Brunei	**All Africa**
Austria	Israel	Spain	Belgium	Latvia	Cambodia	Argentina
Belgium	Italy	Sweden	Bulgaria	Lithuania	Indonesia	Peru
Canada	Japan	Switzerland	Croatia	Luxembourg	Laos	Bolivia
Chile	Korea	Turkey	Cyprus	Malta	Malaysia	Colombia
Czech Republic	Latvia	United Kingdom	Czech Republic	Netherlands	Myanmar	Venezuela
Denmark	Luxembourg	**United States**	Denmark	Poland	Philippines	Saudi Arabia
Estonia	**Mexico**		Estonia	Portugal	Singapore	Iran
Finland	Netherlands		Finland	Romania	Thailand	Iraq
France	New Zealand		France	Slovakia	Vietnam	Kazakhstan
Germany	Norway		Germany	Slovenia		Mongolia
Greece	Poland		Greece	Spain		Pakistan
Hungary	Portugal		Hungary	Sweden		Ukraine
Iceland	Slovakia		Ireland	United Kingdom		**Rest of the world in grey**

The “Africa+” group of countries was attained by withdrawing from the Non-OECD the countries China, India, Russia, ASEAN and Brazil. This was the most approximate value for the African countries which was possible to obtain. The remaining countries not shown on Table 2, are the BRICS countries: Brazil, India, Russia, China and South Africa.

3.2.1 Considered material use factors for low-carbon electricity generation technologies

In order to carry on and present a quantification for the three ETP scenarios produced by IEA some assumptions had to be made either because of the reasons previously listed or because of a time limitation to produce this dissertation. It was assumed that:

- PV is 80% c-SI, 10% a-si, 5% CdTe and 5% CIGS **or** 80% c-SI and 20% thin film
- CSP is 50% Trough and 50% Tower
- Wind Onshore is 100% without permanent magnet (NdFeB) and Offshore 50% as a permanent magnet (PM).

The values presented in Table 3 are the average of all the values found during literature research, this are presented as t/Gw. Some values hado to be corverted from their original unit.

Table 3 - Materials use factor for the electricity generation technologies considered in this thesis. Based on JRC (2011, 2013, 2016); Garcia - Olivares et al. (2012); Ashby, Attwood and Lord, (2012); B.Guezuraga (2012); Corona et al. (2017); Elshkaki & Graedel (2013); Gamesa, (2014); Kavlak (2015); Kleijn and Voet (2010); Kleijn et al, (2018); Ohrlund (2012); Pihl,_et al (2012); Primard, Pierre (2015);Till Zimmermann (2013); USGS (2011); Vestas, (2012); World Bank (2017); Zimmermann (2013);

t /GW	Wind		Solar		Hydro	Geothermal	Ocean	Nuclear	CCS
	Onshore	Offshore	PV	CSP					
Ag			15	17				8	
Al	1,585	1,073	9,534	8,247		11,894	14		
Cd			14					1	
Co								0	8
Cr	3,158	676		2,950	13	64,405	0.31	427	326

t /GW	Wind		Solar		Hydro	Geothermal	Ocean	Nuclear	CCS
	Onshore	Offshore	PV	CSP					
Cu	1,823	7,750	1,765	2,238	69	2,218	446	60	
Dy	8	24							
Fe	130,908	177,373		591,000	25,000	261,431	2,956		
Ga			1						
In			4					2	
Mg			43		2				
Mn	1,191	1,191		3,850	2	4,325			3,761
Mo	184	136		128	3	7,209	0.1	71	8
Nb				70		128		2	100
Nd	39	188							
Ni	748	387		1,370	31	120,155	0.2	256	
Pb	0	5,255	216		5			4	
Pr	20	54							1,145
Se			5						
Sn			372		0.003				
Ta						64			
Tb	1	7							
Te			8						
Ti				13	0	1,634	0.01	2	
Va				2				1	100
W								5	
Zn	5,150	5,750	24	1,025	5				
Cement	94,503	106,080		161,000	1,528,800	106,233			
Zr					0			31	

It is also worth noticing that there are some materials only needed by a specific technology, for example: Ga, In, Te for thin-film PV, W for nuclear energy or Ta for geothermal energy. Others like Al, Cr, Cu, Fe, Mo and Ni are required by most of the considered technologies.

As mentioned, the factors here considered are dependent on a big number of variables such as: technologies and sub-technologies assumed, different sources, consideration or not of materials recycling rates, materials substitution potential, assumed and real-life span of the technologies, annual mine production, mines reserves, stock of electric vehicles, electricity storage capacity, etc. The main limitations of the considered approach are shown in the end of this chapter in Table 15.

It should also be noted that some data was available from similar studies, although the authors of this studies also make their own assumptions, other material use factors here presented vary from source to source, and the rest is not available or publicly accessible.

The share of each type of solar panels were attained from the publication (Moss et al. 2011). This study is a bit outdated especially considering the fast advances made in the last few years. On a more contemporary vision the use of thin films is getting out of the options for the main capacity to be installed.

3.2.2 Electricity generation scenarios for the World, OECD and Non OECD regions

The modern world is still very dependent on fossil fuels, mainly coal and natural gas. These two-fossil fuels are responsible for 44% of the world total gross electricity production as it can be seen in Figure 5 - Share of electricity production sources as installed capacity and gross electricity production, for the World, OECD and Non-OECD in the year 2014. (Source: ETP 2017). It can also be observed that the non-OECD countries are the most dependent, with 28% and 22% of the gross electricity production coming from coal and natural gas respectively. The OECD countries are significantly less dependent on coal but still have a quarter of the total electricity production coming from natural gas and a significant share from nuclear energy.

The three world scenarios developed\ by the IEA can be seen in Figure 6 in terms of the production of electricity per each technology.

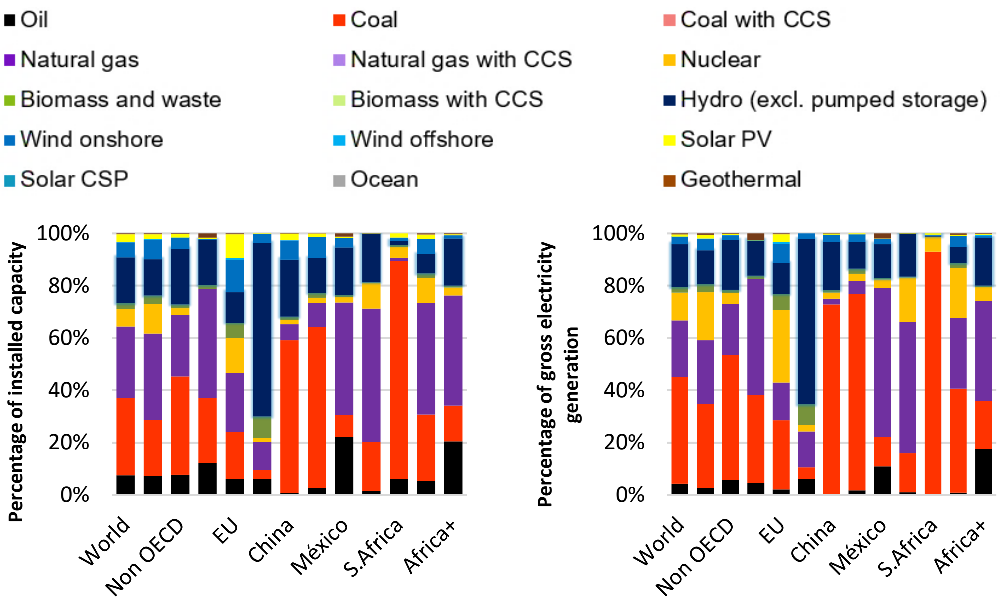


Figure 5 - Share of electricity production sources as installed capacity and gross electricity production, for the World, OECD and Non-OECD in the year 2014. (Source: ETP 2017)

It can be observed that the RTS, which in a sense could also be called a Business As Usual scenario, will create a future electricity mix (by the year 2060) that is still equally dependent on coal and natural gas with just a small portion using CCS technology. Although the renewable technologies are set to significantly increase in the RTS, it is not enough to accomplish the Paris agreement objectives. The 2DS and B2DS are similarly ambitious, with the B2DS presenting a higher share of renewables (78%), as seen in Table 4. The B2DS is pointed out has the only scenario to attain the Paris agreement objectives.

Table 4 - Share of gross electricity generation, share of renewables, total electricity generation and total installed capacity according to the three scenarios up to 2060 for the world

Share of global gross electricity generation	2014	2060		
		RTS	2DS	B2DS
Oil	4.3%	0.7%	0.2%	0.0%
Coal	40.7%	22.2%	0.0%	0.0%
Coal with CCS	0.0%	0.7%	3.8%	2.8%
Natural gas	21.6%	21.9%	4.1%	0.5%
Natural gas with CCS	0.0%	0.0%	2.8%	3.9%
Nuclear	10.6%	9.9%	14.9%	14.8%
Biomass and waste	2.1%	5.1%	5.0%	4.7%
Biomass with CCS	0.0%	0.1%	2.0%	4.2%
Hydro	16.4%	14.7%	16.8%	17.3%
Geothermal	0.3%	1.6%	2.4%	2.6%
Wind onshore	2.9%	10.1%	14.7%	14.5%
Wind offshore	0.1%	2.0%	5.3%	5.3%
Solar PV	0.8%	7.8%	17.2%	17.3%
Solar CSP	0.0%	2.9%	8.9%	10.3%
Ocean	0.0%	0.3%	1.7%	2.0%
% Electricity produced by renewables	**23%**	**45%**	**74%**	**78%**
Total low carbon installed capacity (GW)	**2,762**	**4,464**	**5,275**	**5,379**

Electricity sourced from RES requires much higher values of installed capacity than conventional fossil fuel combustion plants in order to produce the same amount of TWh. Looking at the variations of the electricity generation mixes in the different scenarios and the share of renewables on Figure 6 and Table 4, there is a clear difference between the RTS and B2DS in terms of share of electricity based on renewables and total installed capacity, while the gross electricity production is very similar. Between the 2DS and the B2DS the main difference, besides the fact that it has an overall larger quantity of renewables installed, is the higher use of CCS (with the exception of coal with CCS) which could enable a net zero emission energy system by 2060, according with ETP 2017.

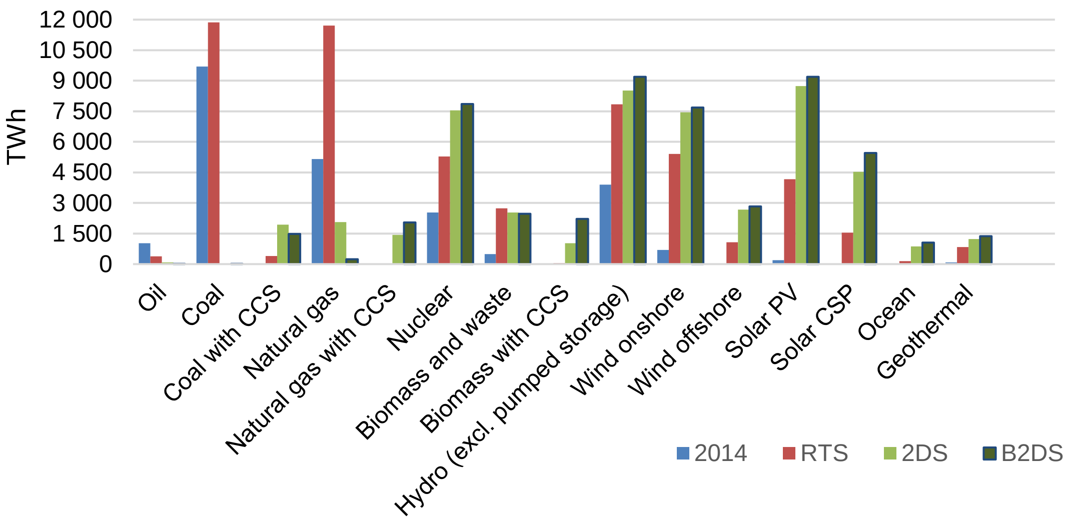


Figure 6 - Comparison of the ETP 2017 scenarios according to the gross electricity generation of each technology.

Table 5 shows the average annual new installed capacity of each low carbon electricity generation technology considered in this study. Once again there is a clear difference between the growth of these technologies according with the RTS and the two other scenarios. Between the 2DS and the B2DS it is possible to observes small differences regarding mainly solar CSP. What is also clear between the RTS and the other two scenarios is the rate of decommissioning of coal plants. While the first scenario decommissions in average one GW a year, the other two withdraw an average of more than 40 GW a year. The RTS will have a major increase in natural gas, which although is not as worse as coal, is still a fossil fuel with harmful emissions. The 2DS does the same but at a smaller rate. Other main differences between the RTS and the two other is the rate at which new solar power capacity is installed annually as well as wind onshore and offshore as it can be observed on Table 5.

Table 5 - Average annual change of installed capacity for electricity generation technologies from 2014 to 2060

Average annual change of installed capacity (GW)	RTS	2DS	B2DS
Oil	- 7	- 1	- 7
Coal	- 1	- 44	- 43
Coal with CCS	1	8	7
Natural gas	58	2	- 14
Natural gas with CCS	0	8	10
Nuclear	7	14	15
Biomass and waste	7	16	32
Biomass with CCS	0	4	8
Hydro*	24	29	34
Geothermal	2	5	5
Wind onshore	43	65	67
Wind offshore	6	15	16
Solar PV	63	146	155
Solar CSP	8	25	31
Ocean	1	7	8

Global installation of new capacity of solar have been steadily increasing over the last years and has recently reached all-time highs in 2017 with a total of 98.9 GW of new capacity installed, of which China was responsible for about 50%. Global wind energy capacity had an increase of 52.5 GW in 2017, but the all-time high of annual installed capacity was in 2015 with approximately 65 GW of new capacity installed, mostly onshore. The two main installers in 2017 were China and the EU with 24.4 GW and 16.8 GW respectively, while the USA installed only 8 GW of new wind capacity.

These global values although high, are mainly derived by China efforts and to a smaller extent the EU. They are in line, or even above the average values of new installed capacity expected by the RTS for these technologies, but still far lower than the values necessary to follow the 2DS and B2DS.

In order to understand the significance of the values on the previous table, Figure 7 gives a better look at how this growth is estimated to happen along the years up to 2060 according to each scenario. The RTS presents a more even annual new installed capacity for the different time gaps, while the 2DS and B2DS tend to grow the annual amount of new installed capacity as time passes. The exception is wind onshore which shows the bigger increase in capacity between the years 2025-2030 for all the scenarios.

The 2DS and B2DS will have a major increase in both solar and wind energy as it can be observed in

Figure 8 and Figure 9. Solar must go from a global installed capacity in 2014 of 178 GW to between 6,394 - 6,697 GW by 2060, in order to follow the 2DS and B2DS respectively. For the RTS, by 2060 it is estimated that less than half of that capacity will be installed.

In terms of wind onshore it is forecast by the ETP that the global installed capacity goes from just 341 GW in 2014 to about 3400 GW in 2060 by the 2DS and B2DS and only around 2400 GW for the RTS. The offshore will add to this value 656 GW in the 2DS and 690 GW in the B2DS and just 251 GW in the RTS which follows nowadays trends.

The maximum installed capacity by 2060 will be if the B2DS is followed and the smallest will be if the RTS continues. This is due to the rate of RES electricity technologies, since in terms of gross electricity production the values are very similar.

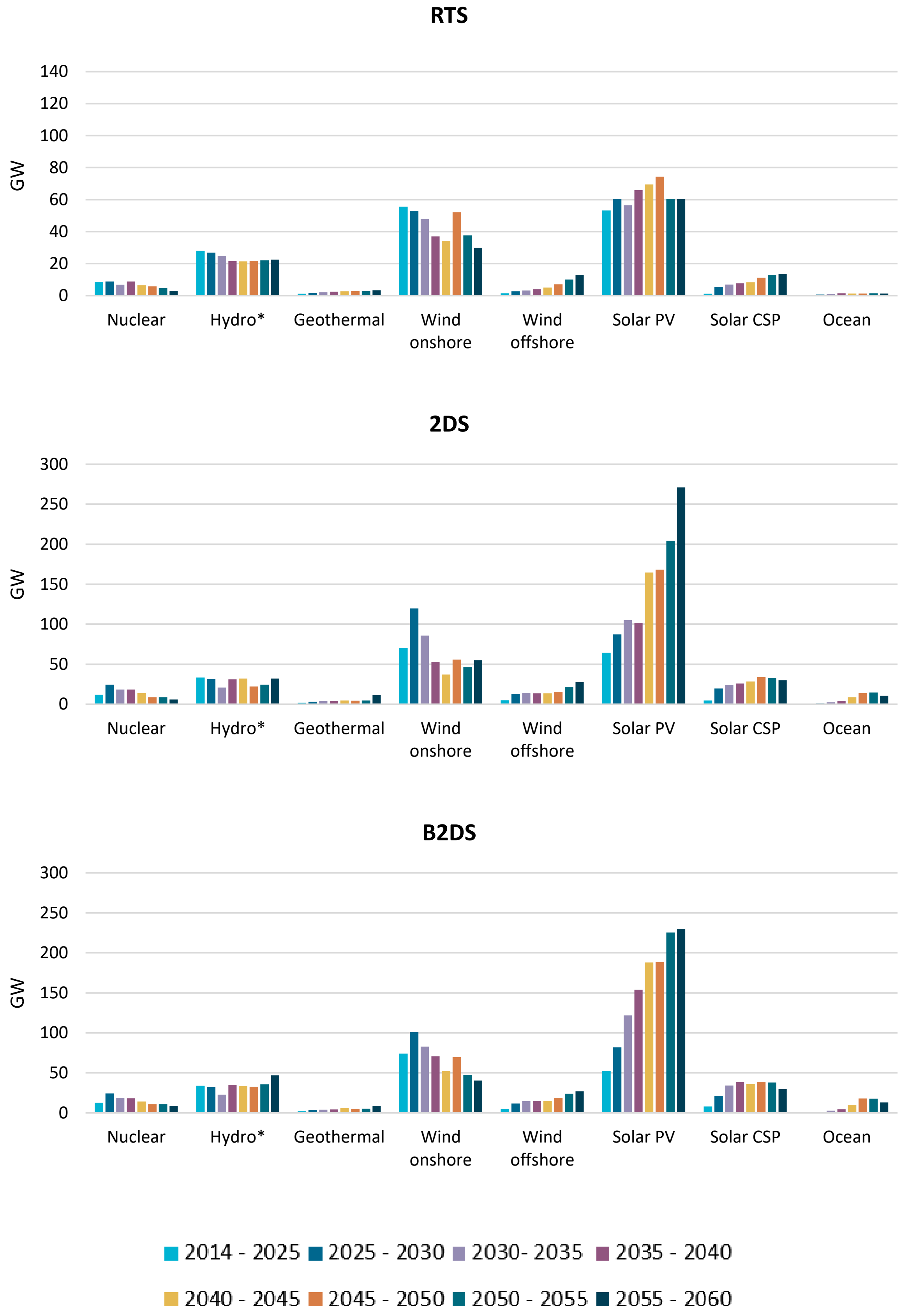


Figure 7 – Annual new installed capacity, in the various time gaps, according to the three scenarios (Source: ETP 2017). * Hydro values exclude pumped hydro.

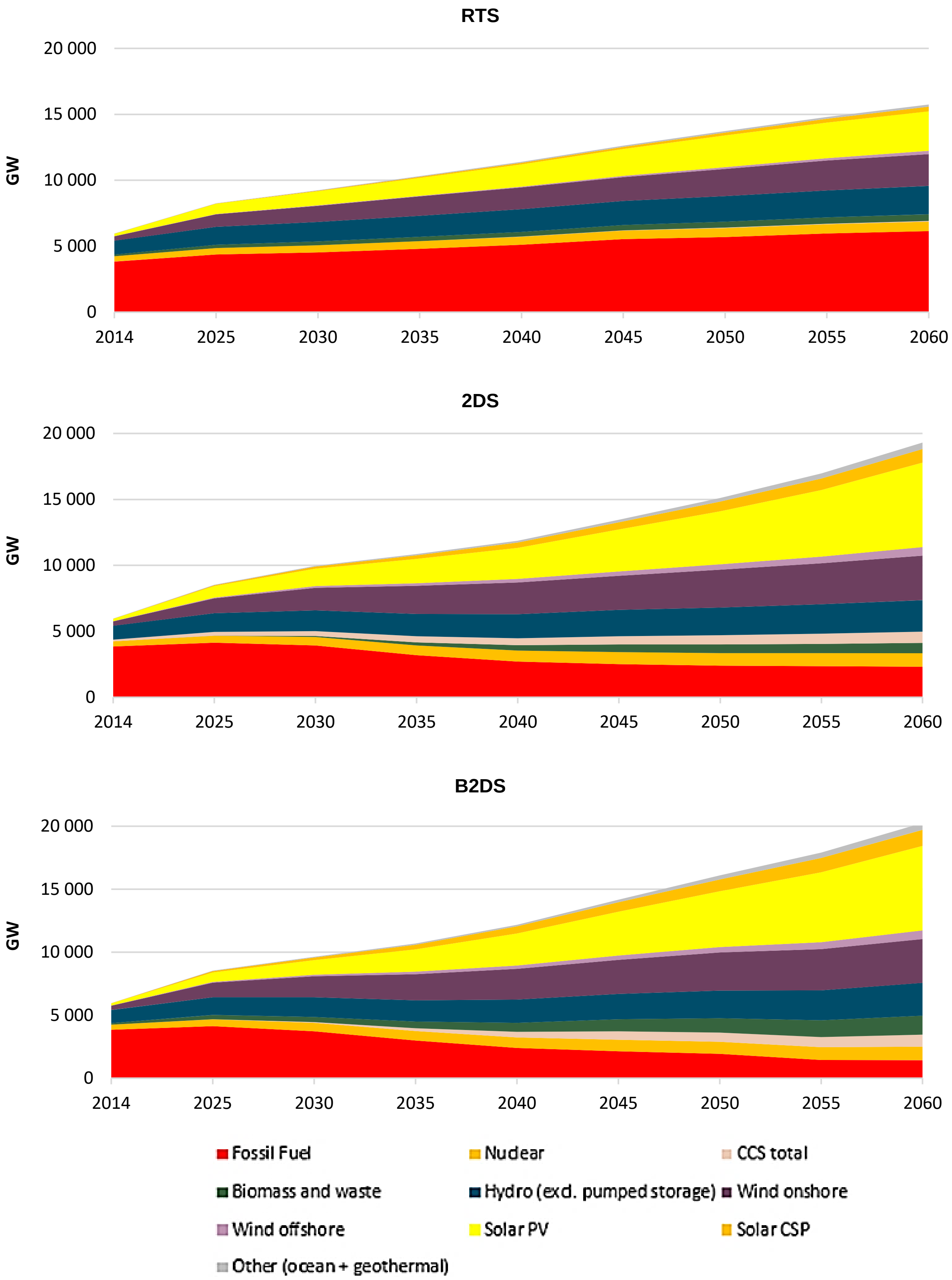


Figure 8 - Comparision of changes in installed capacity of different technologies until 2060 for the three studied scenarios. (Source: ETP 2017)

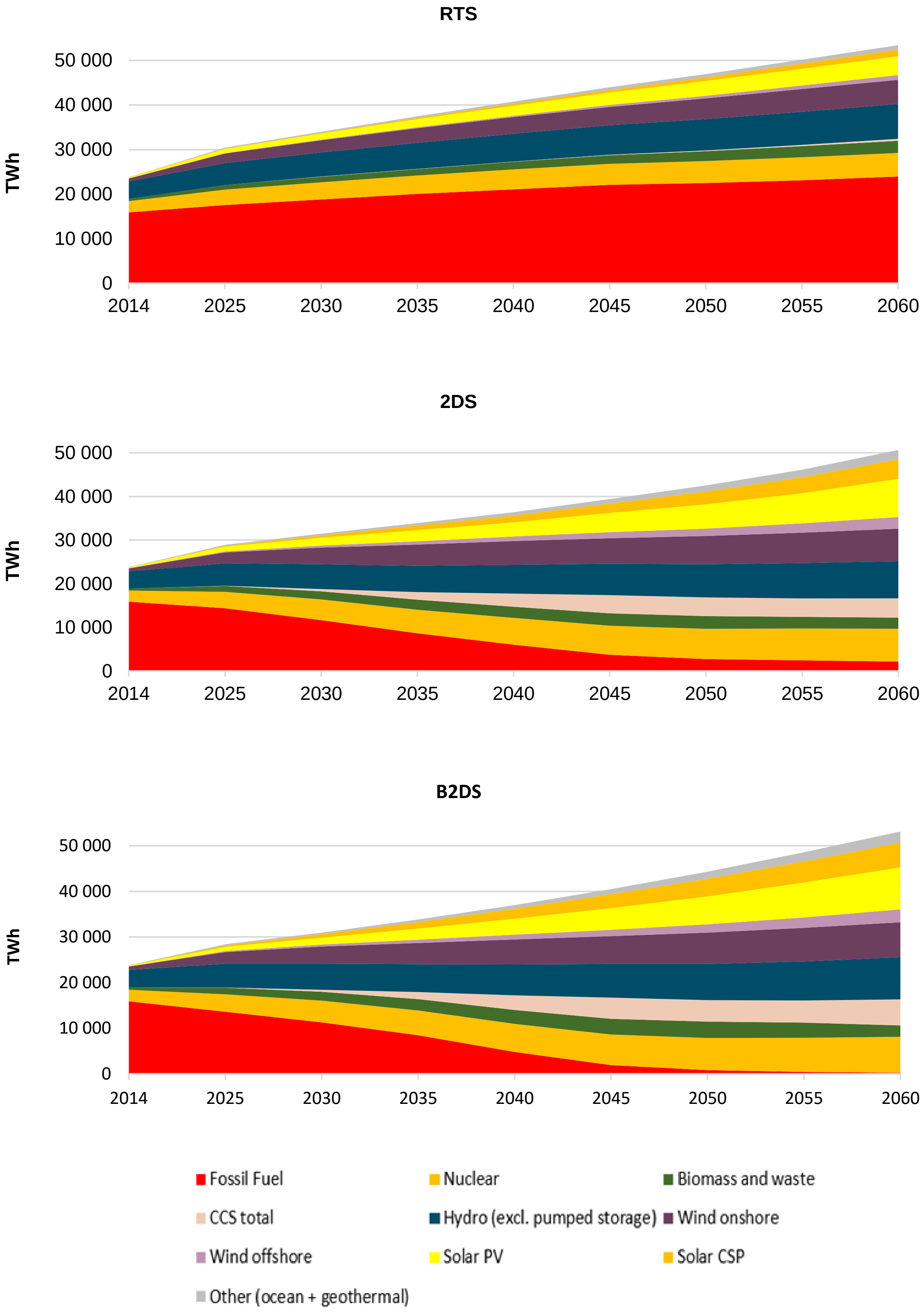


Figure 9 - Comparision of the three scenarios by the changes in gross electricity production of different technologies from 2014 – 2060. (Source: ETP 2017)

3.2.3 Electricity generation scenarios for the BRICS, ASEAN, EU, USA, Mexico and Africa

In this section the regional electricity scenarios are analysed. The regions current state is analysed and compared in terms of the main sources used for the generation of electricity. The regions are then compared with each other having into account the total electricity produced and the share of renewables in each of the three possible outcomes.

Figure 10 shows a comparison between the regions covered by ETP and this study in terms of the share of the global GDP, the share of global emissions and the share of global electricity production. It is possible to observe that China is the most polluting country, considering that it has 13% share of the worlds GDP and 30% of the total emissions while producing 24% of total global electricity. India is similar, but at a smaller scale, showing 3% of global GDP and 6% of global emissions while producing 5% of global electricity. Other countries which present a higher share of global emissions than the share of global GDP are Russia, South Africa and ASEAN. The EU group of countries presents one of the biggest shares of global GDP while presenting one of the smallest levels of emissions and having 13% of global electricity production. The USA also follow a similar pattern, as well as Brazil with 3% of GDP, 1.5% of global emissions and 2,5% of global electricity production. By observing **Figure 11** the analysis gets reversed once the population of each region is examined.

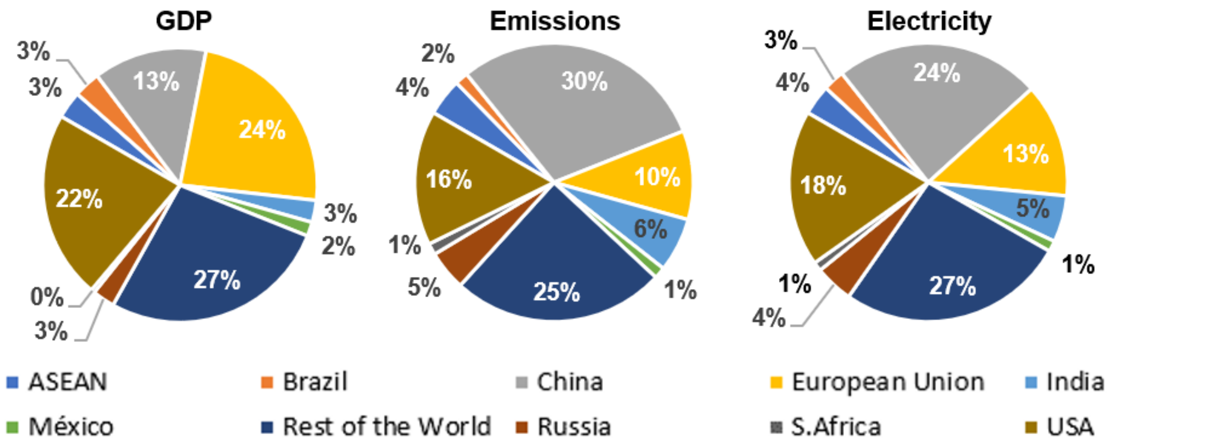


Figure 10 - Comparison of regions by share of global GDP (left), share of global emissions (middle) and share of global electricity production (right) for the year 2014 (Source: IMF, 2018 and ETP 2017)

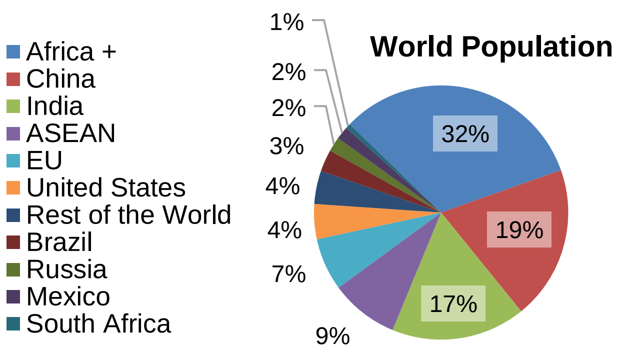


Figure 11 - Share of world population of each region. World population in 2015: 7,207,361 thousand people. (Source: United Nations Population Division, 2015).

China has the biggest share of emissions, but it also has 20% of the earth´s population. Another example is India, which is responsible for 6% of the total worlds emissions has 17% of the global population. On the other end regions like the USA and EU with 4% and 7% of the world population, respectively, are responsible for a much larger share of emissions per capita. What is concluded here is that in terms of values per capita, the richest countries are the ones which have higher values of emissions, whereas the poorest like India have very low emissions compared its population.

To get a better look at the regions considered in this study, a comparison was made of the electricity generation mixes as seen in Figure 12. It's possible to conclude that the countries China, India and South Africa are highly dependent on coal which backs the level of emissions previously seen. Brazil is the country with most RES electricity installed in 2014, having 63% of their gross electricity production coming from hydro energy alone. The EU has the largest share of nuclear (28%) than any other region and the more wide-ranging sources of RES electricity. The ASEAN, Russia and Mexico get most of the electricity produced from natural gas. The countries of Africa + have 18% of their electricity coming from oil, and Mexico also has a considerable share of oil in its mix (11%)

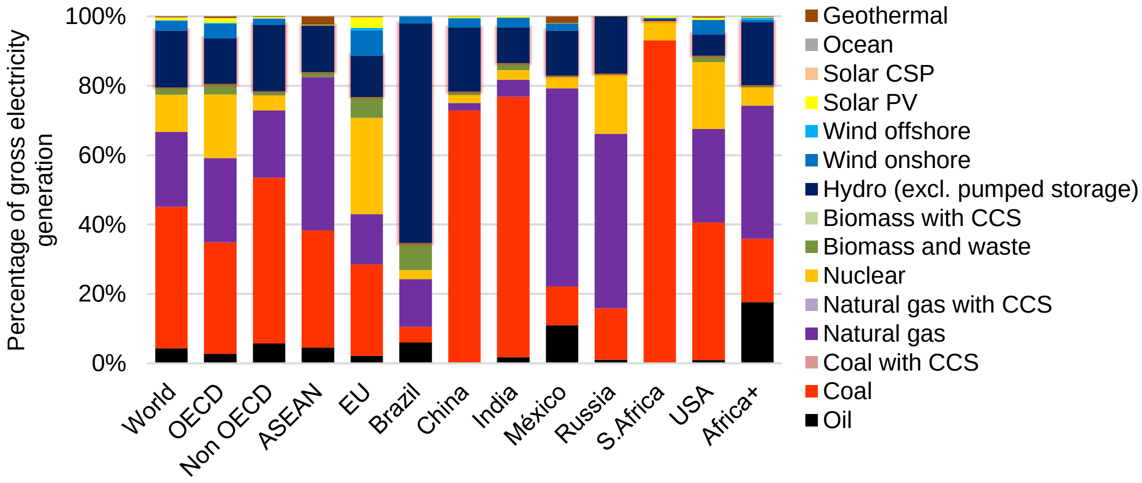


Figure 12 - Comparison of electricity production mixes of the different regions for the year 2014 (Source: ETP 2017)

In Figure 13 it is possible to observe the changes in the future share of global electricity production according with the three scenarios of the IEA in ETP. In the most ambitious scenario, the B2DS, China will reduce its share to 19%, the EU to 7%, the USA to 12% and Russia to 3%. All the remaining regions will increase the production of electricity, specially India which is envisioned to produce from 5% to 13-15% of the world electricity production by 2060, depending on the scenario followed.

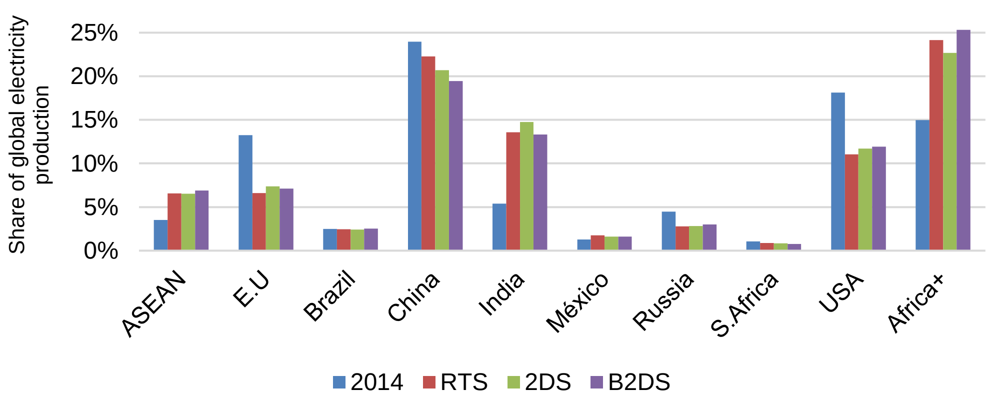


Figure 13 - Share of world electricity production per region, in 2014 and according to the 3 scenarios (Source: ETP 2017)

According to the ETP, regions that do not belong to the OECD are those who will have a higher growth in electricity demand up to 2060. Led by India (with growth between 450% and 481%), followed by ASEAN (with a growth between 294% and 336%) and in third place Africa+ (with a growth between 262% and

278%). Worldwide it is expected that electricity consumption more than doubles up to 2060 (with a growth between 113% and 124%). This data can be observed in Table 6 in its absolute values.

Table 6 - Gross electricity production in the year 2014 and 2060 according to the three ETP scenarios (TWh)

TWh	2014	RTS	2DS	B2DS
World	23,819	53,429	50,662	53,123
OECD	10,793	14,084	13,788	14,182
Non-OECD	13,048	38,389	35,413	37,486
ASEAN	839	3,518	3,308	3,657
EU	3,159	3,519	3,730	3,783
Brazil	591	1,317	1,227	1,343
China	5,706	11,900	10,481	10,342
India	1,287	7,263	7,476	7,086
México	301	942	816	863
Russia	1,062	1,493	1,423	1,596
S. Africa	269	419	419	406
USA	4,319	5,911	5,923	6,341
Africa+	3,563	12,898	11,499	13,462

The share of renewables that each scenario estimates up to 2060 can be observed in Figure 14. It was previously presented that the world could have between 45% and 78% of the total gross electricity production coming from renewable sources. In terms of the studied regions, as previously noted, Brazil is by far the region with the biggest share of renewables in its electricity mix and is expected to stay on top, going from 73% in 2014 to 97% of total gross electricity production coming from renewable sources in 2060, according with the 2DS and B2DS.

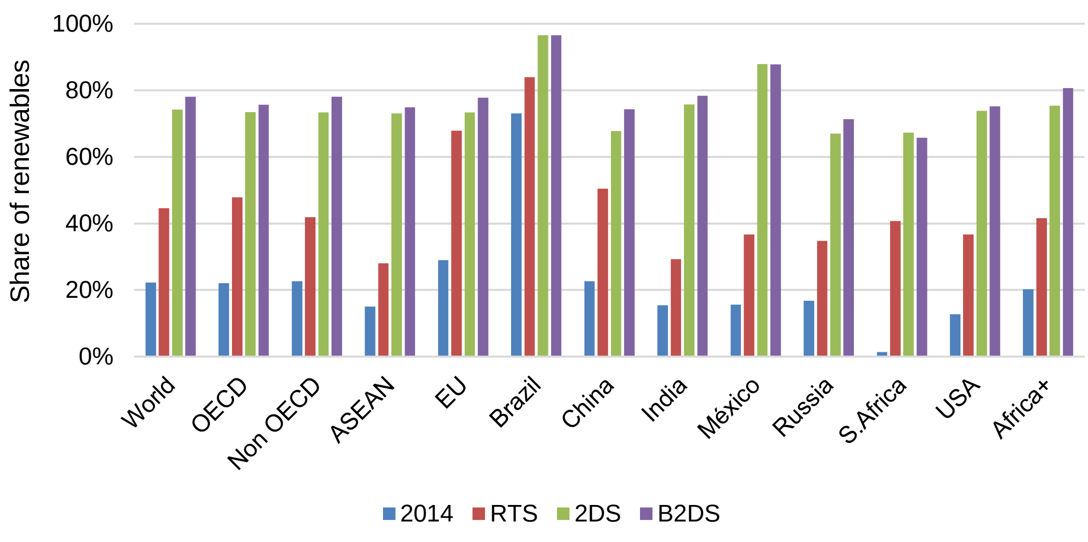


Figure 14 - Percentage of RES electricity per region in the three scenarios up to 2060 (Source: ETP 2017)

The biggest challenges come from the same regions which will have the biggest growth in electricity consumption and are also the more dependent on fossil fuels for electricity generation. Those regions are India, ASEAN, Africa +, China and Mexico. South Africa presents the biggest difference in the share of renewables between 2014 and 2060, from 1% of its electricity coming from RES to 67% in the 2DS.

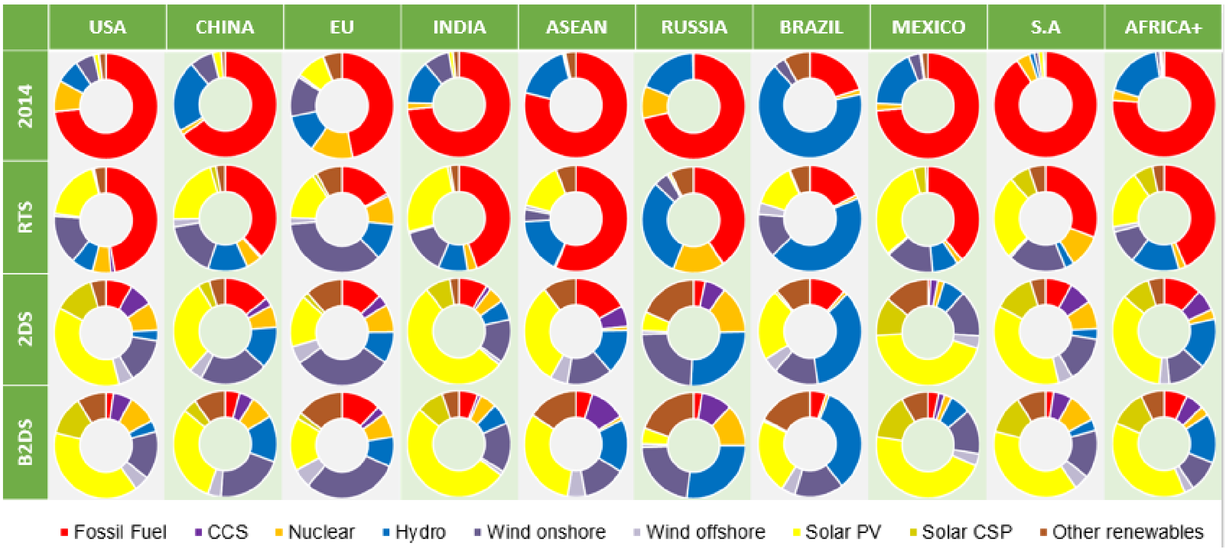


Figure 15 - Comparison of the electricity generation mixes in the year 2014 and the year 2060 according with the three scenarios. (Source: Author ellaboration on ETP 2017)

It is possible to observe in Figure 15 that in the more ambitious scenario (B2DS) almost all use of fossil fuels for the generation of electricity in 2060 is with CCS. The same does not happen with the generation of electricity according to the 2DS scenario, it is possible to observe that natural gas remains the source of generation of about 2000 TWh electric power. Yet none of the previously spoken scenarios is comparable to the RTS which keeps fossil fuels (coal and natural gas) as the main sources of electricity production in 2060, with the exception of the EU and Brazil. In terms of renewable sources both the 2DS scenario and the B2DS strongly bet on wind energy (onshore) and solar power (PV and CSP)

In 2014 the share of fossil fuel for the generation of electricity is excessive in all country's mixes, with the exception of Brazil. Globally electricity demand is expected to at least double by 2060, some examples of regions expected to increase a lot are India (1.3 to 7.2 TWh /yr.), Africa+ (3.5 to 13,4 TWh /yr.) or ASEAN (0.8 to 3.6 TWh /yr.).

3.2.4 Scenarios for deployment of hybrid and electric vehicles and material use factors

Hybrid and Electric vehicles are an important part of the transition to a low carbon energy system. Observing Figure 16 and comparing it with Figure 17 and

Figure 18, it can be said that the RTS will have a higher number of vehicles, with the majority being internal combustion engines (ICE) by 2060. The ICE start decreasing their numbers between the years 2045-2050 according to the RTS, but overall for the time frame of the scenarios, they still grow by 14% for gasoline, 46% for diesel and 171% for compressed natural gas and liquefied petroleum gas (CNG/LPG) vehicles, as it can be seen in Table 7.

Table 7 - Comparison of internal combustion vehicles growth in the three scenarios, from 2014 to 2060 (Source: ETP 2017)

2015-2060 growth	RTS	2DS	B2DS
Gasoline ICE	14%	-56%	-89%
Diesel ICE	46%	-58%	-89%
CNG/LPG	171%	-3%	-44%

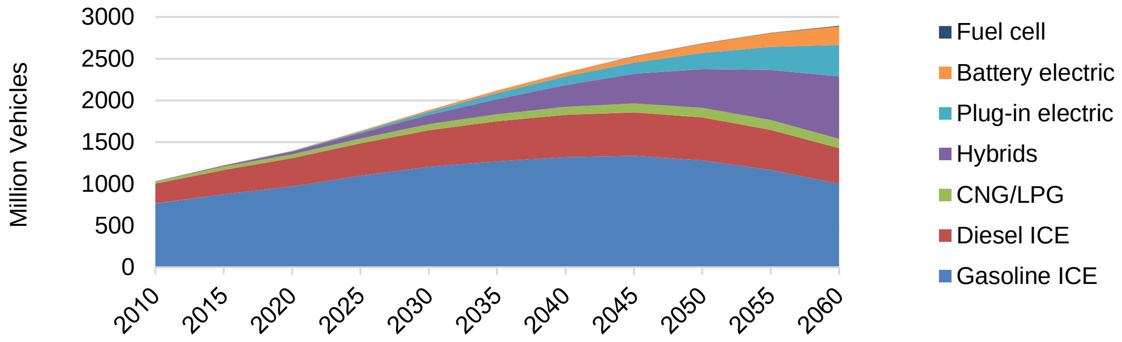


Figure 16 - Evolution of the stock of vehicles up to 2060, according with the RTS (Source: ETP 2017)

In the 2DS scenario the ICE vehicles start decreasing after the year 2025 and overall decrease the number of all the vehicles that use fossil fuel, as seen in Table 7. Only by the year 2055 will the electric vehicles (PHEV and BEV) be a greater share of the world stock of vehicles than the ICE (Gasoline and Diesel). This scenario bets on the adoption of the PHEV at higher rates than BEV.

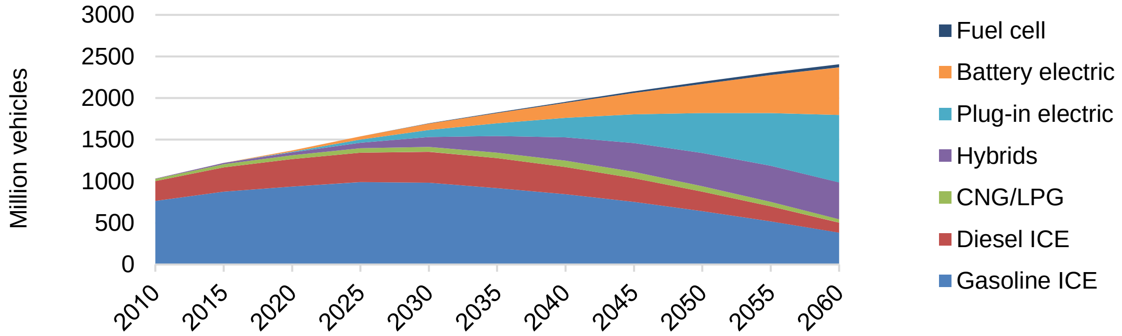


Figure 17 - Evolution of the number of vehicles until 2060, according with the 2DS (Source: ETP 2017)

The most ambitious scenario reaches a higher number of EV's than ICE by the year 2045, with 33% of the total stock being gasoline and diesel vehicles compared with 48% of combined PHEV and BEV.

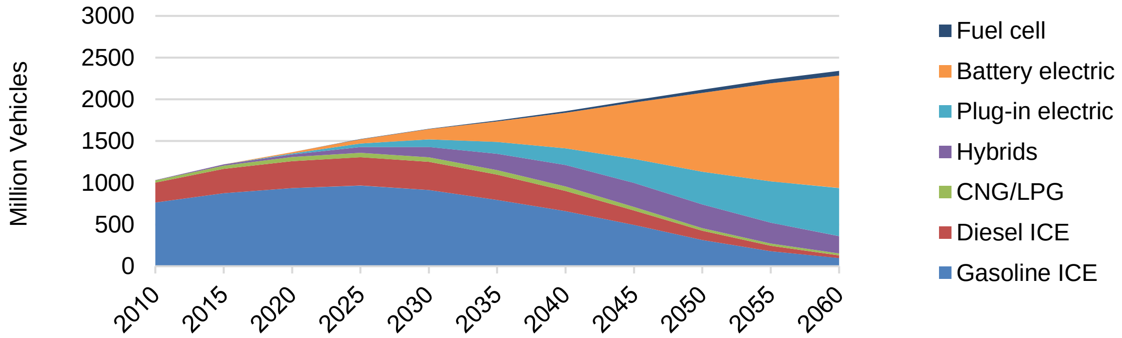


Figure 18 - Evolution of the amount of hybrid and electric vehicles until 2060, according to the three scenarios (Source: ETP 2017)

Just as the scenarios for the electricity generation technologies, there is also big differences between the paths of the three scenarios for the global stock of vehicles as it can be seen summarized in Figure 19.

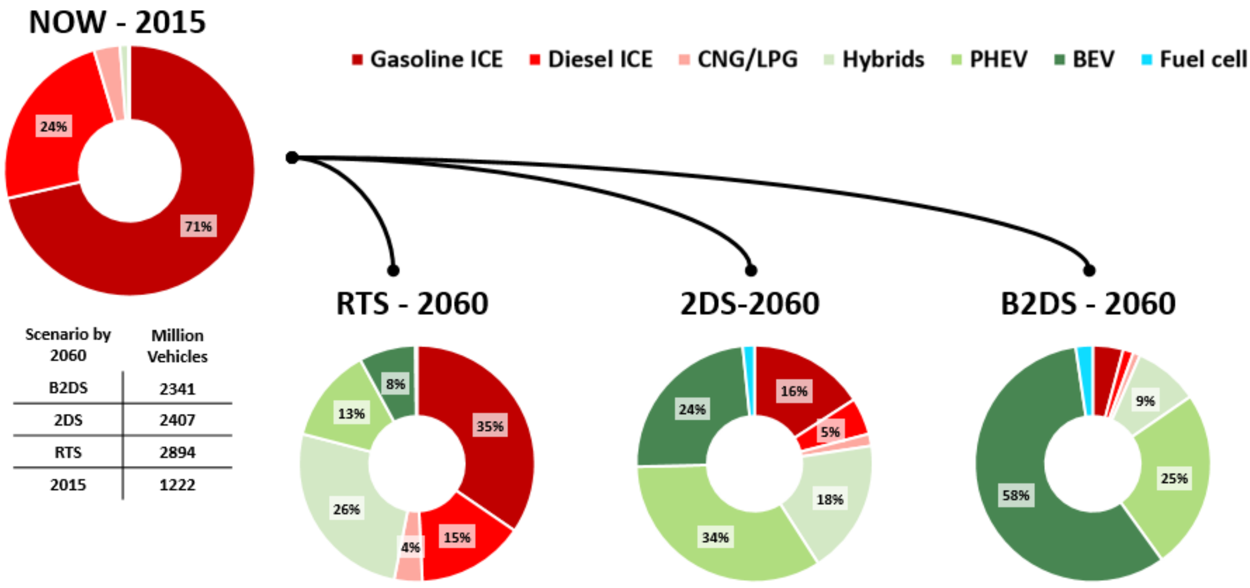


Figure 19 - Three possible outcomes by 2060, according with the IEA scenarios (Source: ETP 2017)

In Table 8 the material use factors (kg/vehicle) used for the quantification of the total demand for materials in EV until 2060 are shown. The use of cobalt, graphite, lithium, nickel and titanium is what separates HEVs and PHEVs from BEVs, due to the use of larger batteries. It is important to note that HEV do not work with electricity alone, but mainly with fossil fuels. Also, PHEV have 2 engines, one electric and one internal combustion, and BEV work fully on electricity.

Table 8 - Material use factors used in the quantification of total material requirements for EV's. (World Bank, (2017); Kleijn et al, (2018); JRC (2013,2016)

kg/Vehicle	HEV	PHEV	BEV	Kg/Vehicle	HEV	PHEV	BEV
Al	105	119	244	**La**	0.58	0.58	0.58
B	0.03	0.04	0.09	**Pb**	6.9	6.9	7.45
Co	0.58	1.47	6.50	**Li**	0.15	1.55	8.586
Cu	0.74	26.97	35.54	**Mn**	0.625	5.13	30.035
Dy	0.161	0.19	0.21	**Nd**	0.68	1.002	1.62
Ga	0.0025	0.0025	0.0025	**Ni**	3.335	3.985	23.325
Ge	0.00004	0.00004	0.00004	**Pd**	0.00072	0.00072	0.00072
Au	0.00018	0.00018	0.00018	**Pr**	0.045	0.133	0.06
C	0.90	14.08	51.43	**Ag**	0.006	0.006	0.006
In	0.00004	0.00004	0.00004	**Tb**	0.015	0.015	0.015
Fe	1016	1047	1295	**Ti**	0.405	3.315	19.39

The study by JRC of 2016 is very detailed in a smaller number of materials. The study of Kleijn et al, 2018 includes values for the following materials: Fe, Al, Cu, Ni, Cr, In, Nd, Dy, Li, Zn, and Pb. The World Bank, 2017 study has values for a large number of materials but is not as specific as the two previous studies regarding which type of low carbon vehicles use each type of material. The values are presented as a range of values and sometimes specified for which type of vehicle.

3.2.5 Scenarios for deployment of electricity storage and material use factors

As it was written before, IEA ETP provides only data of the estimated electricity storage capacity for the whole world. To better quantify the regional demand with was necessary to distribute this capacity. Electricity storage will be used mainly at home and when there is a use of variable renewables (wind and solar power). Using this assumption, the distribution of electricity storage capacity was made by considering a similar distribution as of the amount of electricity produced by this type of technologies in each region. Another assumption was the values for the RTS storage capacity - once again to have a more complete quantification of total demand for the three scenarios, it was assumed that the RTS would grow in the same proportions than exist between the 2DS and B2DS.

As it can be observed in Figure 20, the maximum global storage capacity will be one TWh according to the B2DS. The 2DS will have a storage capacity around half of the B2DS and the RTS around half of the 2DS.

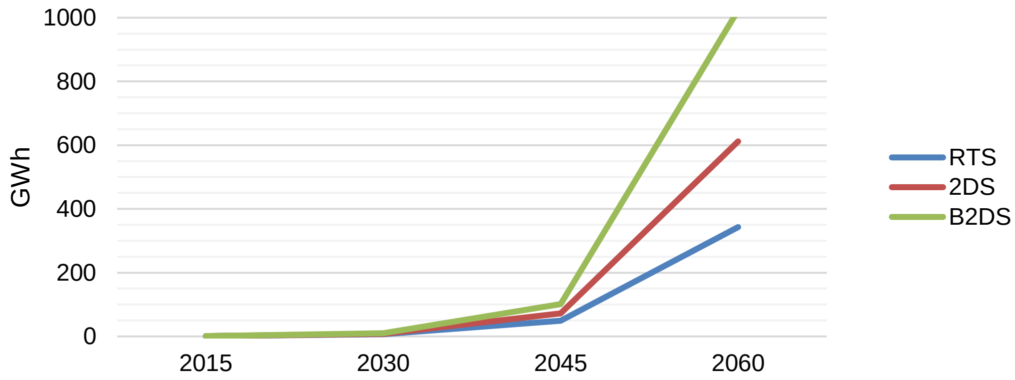


Figure 20 – Global storage capacity according to the three scenarios up to 2060 (Source: ETP 2017)

Overall these values are perhaps conservative, and it is projected that they will have small impact on the overall demand of any given scenario. It was assumed that 100% of the storage capacity would be made out of generic Li-Ion batteries. Table 9 shows the materials considered and the respective material use factor retrieved from the literature.

Table 9 - Material use factors used in the quantification of total material requirements for energy storage. Ellingsen et al, (2014); World Bank, (2017); JRC (2016)

Lithium-Ion batteries	t /GWh
Al	908
Co	396
Fe	1,239
Li	529
Mn	463
Ni	463
C	1,886
Cu	1,429

3.3 Methodology for assessing potential materials supply bottlenecks for deployment of low carbon technologies

3.3.1 World materials production and reserves

The low carbon energy technologies considered in this dissertation are estimated to create a demand for a total of thirty-one materials - this is if the rare earth elements are grouped into one. In Table 10 it is possible to observe the size of the current known reserves and the rate at which they are being consumed. It is also possible to estimate the number of years of mine production there still is, considering 2016's global annual production of each material as a constant over time. In red are the materials which present an estimated number of years of production lower than the time gap of this analysis (2014-2060)

Table 10 - Assessment of the 31 materials considered in this study in terms of global annual production, global reserves, estimated remaining years of production and percentage of reserves annually mined in 2016. Source: (Reichl, Schatz, and Zsak 2017) (USGS 2017b)

Element	2016 Global Annual Production (t)	Reserves World (t)	Years of Production	% of reserves mined annually
	(A)	(B)	(B/A)	(A/B)
Bauxite	284,933,806	30,000,000,000	105	1%
Boron	4,310,367	1,100,000,000	255	0%
Cadmium ①	26,011	NA	NA	NA
Chromium	13,092,060	510,000,000	39	3%
Cobalt	126,234	7,100,000	56	2%
Copper	20,417,159	790,000,000	39	3%
Gallium ②	194	NA	NA	NA
Germanium ③	122	NA	NA	NA
Gold	3,214	54,000	17	6%
Graphite	1,126,001	270,000,000	240	0%
Indium ④	807	NA	NA	NA
Iron	1,575,123,716	83,000,000,000	53	2%
Lead	4,703,327	88,000,000	19	5%
Lithium	78,549	16,000,000	204	0%
Magnesite	26,010,251	7,800,000,000	300	0%
Manganese	15,414,509	680,000,000	44	2%
Molybdenum	279,309	17,000,000	61	2%
Nickel	1,953,503	74,000,000	38	3%
Niobium	91,827	4,300,000	47	2%
Palladium ⑤	211	69,000	328	0%
Selenium	3,360	100,000	30	3%
Silver	27,269	530,000	19	5%
Tantalum	1,694	110,000	65	2%
Tellurium	390	31,000	79	1%
Tin	340,145	4,800,000	14	7%
Titanium	6,877,550	930,000,000	135	1%
Tungsten	85,789	3,200,000	37	3%
Vanadium	85,729	20,000,000	233	0%
Zinc	12,524,698	230,000,000	18	5%
Zircon	1,383,349	74,000,000	53	2%
RE	124,735	120,000,000	962	0%

① - The cadmium content of typical zinc ores averages about 0.03%.
②- Only a portion of the gallium present in bauxite and zinc ores is recoverable, and the factors controlling the recovery are proprietary. Therefore, an estimate of reserves is not possible.
③- Data on the recoverable germanium content of zinc ores are not available.
④- Quantitative estimates of reserves are not available.
⑤- Data on reserves is only available for the all Platinum Group Metals (PGMs)

Au, Pb, Ag, Sn and Zn present the lowest estimated years of production, all with less than twenty years if the reserves remain unchanged and the annual production stays the same. All the numbers in red represent and number of estimated years of production inferior to the time frame of the ETP scenarios (less than 40 years).

The USGS defines resources as "a concentration of naturally occurring solid, liquid or gaseous material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible," while reserves are defined as "that part of the reserve base which could be economically attractive or produced at the time of determination." In this study resources were not part of the analysis.

Figure 21 along with Table 11 shows how the rate of production has increased since 2000. From 2000 to 2016, Iron and Ferro-Alloy Metals have a growth superior to 150%, while non-ferrous metals almost doubled.

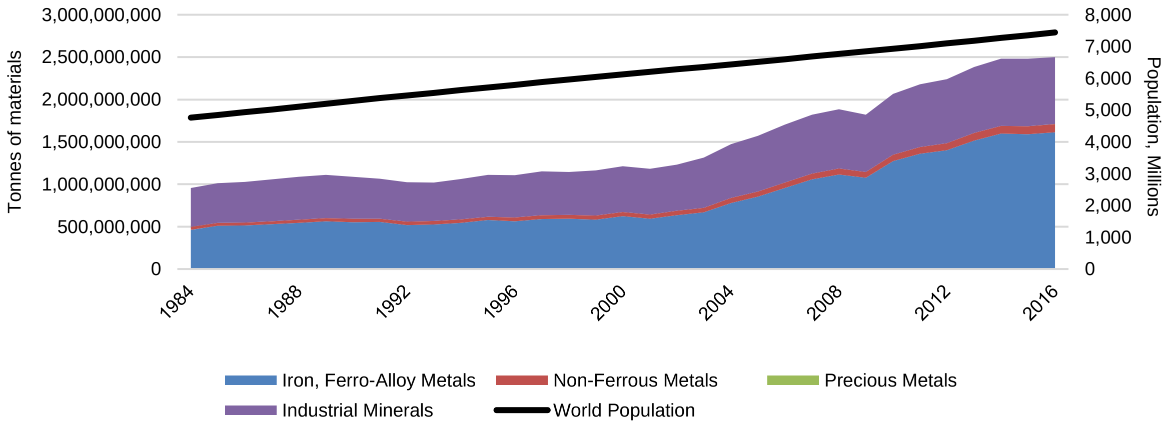


Figure 21 - Growth of production of different mineral categories and global population. Source: (www.world-mining-data.info and UN Population Division 2016 dataset)

Note:

Iron and Ferro-Alloy Metals: Iron, Chromium, Cobalt, Manganese, Molybdenum, Nickel, Niobium, Tantalum, Titanium, Tungsten, Vanadium
Non-Ferrous Metals: Aluminium, Antimony, Arsenic, Bauxite, Bismuth, Cadmium, Copper, Gallium, Germanium, Lead, Lithium, Mercury, Rare Earth Minerals, Rhenium, Selenium, Tellurium, Tin, Zinc
Precious Metals: Gold, Platinum-Group Metals (Palladium, Platinum, Rhodium), Silver
Industrial Minerals: Asbestos, Baryte, Bentonite, Boron Minerals, Diamond (Gem/Industrial), Diatomite, Feldspar, Fluorspar, Graphite, Gypsum and Anhydrite, Kaolin (China-Clay), Magnesite, Perlite, Phosphates (incl. Guano), Potash, Salt, Sulphur, Talc (incl. Steatite and Pyrophyllite), Vermiculite, Zircon

The materials considered in this study constitute most of the Iron and Ferro-Alloy Metals, Non-Ferrous Metals and Precious Metals categorys and a few of the Industrial minerals category. The two first categories had the largest increase in production between 2000- 2016, more than doubling the ammount mined.

Table 11 - Growth of production of different mineral categories and of global population; Sources: *(*www.world-mining-data.info *and UN Population Division 2016 dataset)*

Commodities	Growth 1990-2016	Growth 1990-2000	Growth 2000-2016
Iron, Ferro-Alloy Metals	**192%**	13%	159%
Non-Ferrous Metals	**177%**	42%	95%
Precious Metals	**112%**	44%	47%
Industrial Minerals	**72%**	17%	47%
Mineral Fuels	**72%**	20%	43%
World Population	**56%**	29%	22%

In Figure 22 is presented the share that each region has of the global annual production. This is relevant to understand which regions are in a better position to satisfy the demand of materials for the energy transition to a low carbon energy.

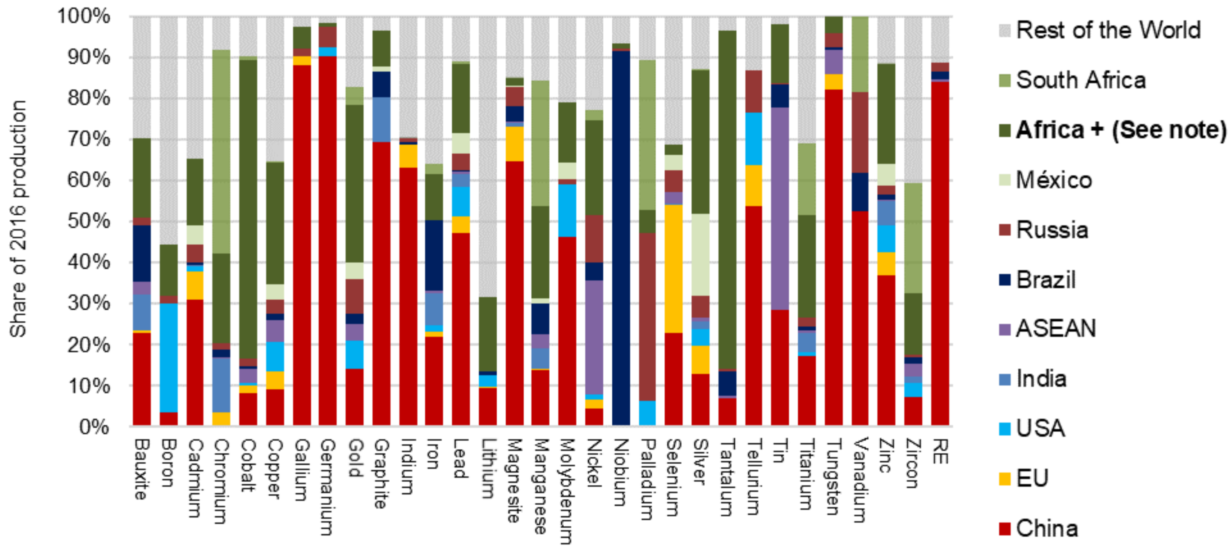


Figure 22 - Share of 2016 World mine production by ETP region. Note: Here Africa + does not include South Africa. (Source: authors ellaboration over www.world-mining-data.info)

By observing Figure 22 and Figure 23 it becomes clear the strength of China for the transition to a low carbon energy system and for supplying the world. The case of rare earths is the most mediatic, since is one of the "worst" cases, having China 84% of the global production in 2016. But there are other cases of which China has most of the global annual production such as: Ga (88%), Ge (90%), Graphite (69%), In (63%), Pb (47%), Mg (65%), Mo (46%), Te (54%), W (82%), Va (52%).

There are examples of other countries which control most of the global annual production of certain materials. Brazil has 91% of Indium, ASEAN has 49% of Sn, Africa+ (without South Africa) has 82% of Ta, 73% of Co, 38% of Au, South Africa has 49% of Cr. In the case of boron, Turkey has 42% of global production. In the case of copper and lithium Chile is the world largest producer (with 27% and 40% respectively) and Peru the second largest for copper (with 12%). These last countries are inserted in the" rest of the world" group.

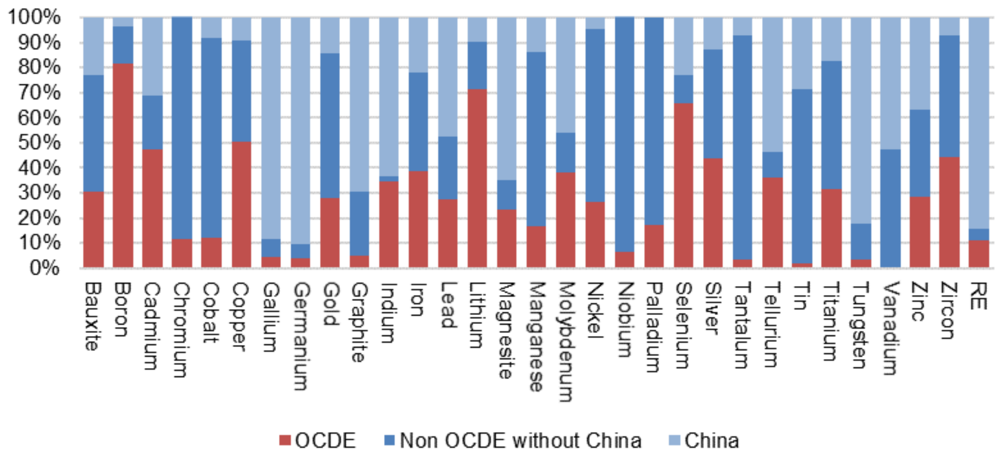


Figure 23 - Share of mining production of different metals for OCDE and non OCDE countries not including China and China (Source: authors ellaboration over www.world-mining-data.info)

After observing Figure 23 it is clear that the Non OECD countries produce most of the materials required and inside this group China is the biggest world producer of most minerals.

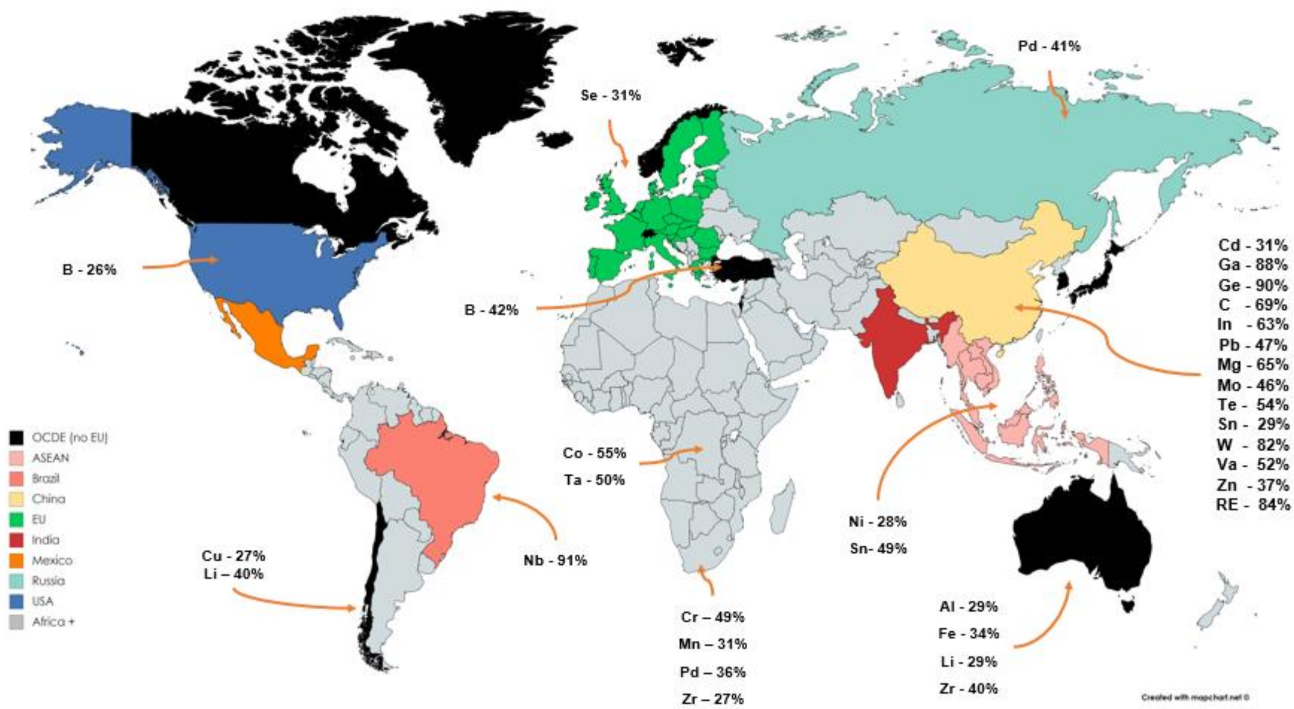


Figure 24 –World largest producers of the 31 materials considered. (Source: authors ellaboration over www.world-mining-data.info)

3.4 Energy consumption from materials extraction

The initial aim of this thesis was to present a full quantification of the impacts of extracting different materials, but this was not possible due to lack of accessible data. Even though some research exists made by (Norgate and Haque 2010) it unfortunately only presents data for three materials: Iron, Bauxite and Copper. It is explained by Norgate and Hague that this type of assessment related to the extracting phase is rare due to the lack of available data and the small impact it has in the complete life cycle of a material or finished product. The overall values presented by the authors can be seen in Table 12. Some consumption of diesel and electricity presented by the authors was not used as it was related to a specific case of train and ship transport in Australia.

Table 12 - Overall consumption of electricity, diesel and water for extraction phase; Source: (Norgate and Haque 2010)

Mineral	Electricity		Diesel		Water		Type of mine
Iron	3.0	kWh/t ore	88.5	MJ/t ore	0.2	m3/t ore	Surface
Bauxite	1.9	kWh/t ore	38	MJ/t ore	0.3	m3/t bauxite	Surface
Copper	46.4	kWh/ t ore	115	MJ/t ore	0.5	m3/ t ore	Underground

The first approach was to quantify the all the materials using an average of the values on Table 12. After researching the literature, it became clear that most minerals function as by-products of others as it can be seen in Figure 25. This way , the only materials for which the energy consumption was calculated were those present on the most inner circle of the figure, since the materials in the remaining circles function as co-products of the main ones. (Verhoef, Dijkema, and Reuter 2004).

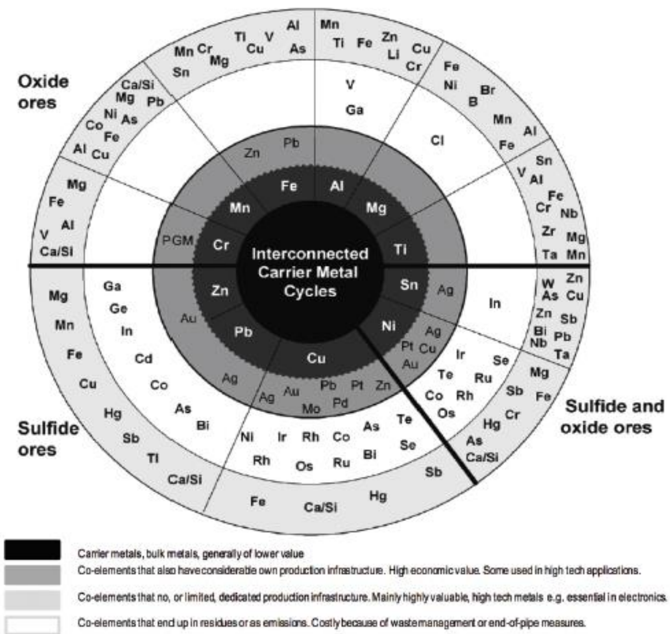


Figure 25 - Interconnected carrier metal cycles; Source:(Verhoef et al. 2004)

For the materials aluminium, copper and iron it was used directly the values of Norgate and Hague. For the remaining it was performed an average of all the relevant factors from the same authors, which can be seen in Table 13.

Table 13 - Factors used for calculating energy demand from metal extraction. Source: (Norgate and Haque 2010)

Mine consumption (70% surface and 30% underground)		
Water	0.340	m3/ t ore
Diesel	95.1	MJ/ t ore
Electricity	0.000000016	TWh / t ore

It´s important to notice that all the values in the table above are in tonnes of ore and that all the quantification of demand is realized as metal content. This way the values for the average global ore grade for each material had to be researched and divided by the total weight of materials quantified. Most of the values were retrieved from (Elshkaki et al. 2018)

3.5 Overview of main methodological limitations

It is impossible to predict the future and the aim of this study was to analyse the ETP scenarios by crossing variables. What was obtained was an estimated effect of the ETP scenarios and not a precise prediction. In this subsection the main limitations are shown in Table 14. This study is dependent on a significant number of variables such as: technologies and sub-technologies assumed, material use factor from different sources, materials recycling rates, materials substitution potential, life span of the technologies, annual mine production, mines reserves, stock of electric vehicles, electricity storage capacity, etc.

Some data was available from similar studies although the authors of this studies also make their own assumptions, others vary from source to source and the rest is not available or not publicly accessible. To carry on and present a quantification for the three ETP scenarios produced by IEA some assumptions had to be made either because of the reasons listed above or because of a time limitation to produce this dissertation. Still this dissertation may serve as a basis for a more profound future analysis.

Table 14 - Assumptions made

Assumption	Description	Effect
Material	It was assumed that the material efficiency of the different technologies remains constant over time. It was also assumed that the amount of materials used per unit of installed capacity of all technologies is maintained constant over time	**Overestimation**
Materials Recycling Rates and Substituion	The material recycling rates did not enter the quantification of the total materials required until 2060, nor did the potencial for substituiton.	**Overestimation**
Material use in other applications	Data of the use of the same materials in other applications was not taken into account.	**Underestimation**
Life span of low carbon technologies	It was assumed that the lifetime of each technology is integrated into the projections of the ETP 2017	**Underestimation**
Sub-technologies mix	**PV**: 80% c-SI, 10% to-si, 5% CdTe and 5% CIGS **CSP**: 50% Trough and 50% Tower **Wind**: Onshore 100% without PM; Offshore 50% without PM and 50% with PM **Batteries**: 100% Ion-Lithium Batteries	**Unknown**
Installed capacity by region	When the values were only made available by the IEA to the world, a distribution was carried out according to the regions share of gross world electricity production. For the batteries it was calculated based on the share of the variable renewables (wind and solar)	**Unknown**

Assumption	Description	Effect
Electric vehicles	Here it was assumed that all vehicles are passenger vehicles, encompassing two and three-wheeled vehicles, buses and trucks. Also, the distribuiton of the vehicles in the regions was made using the electricity use in transport provided by the IEA .	**Unknown**

Quite a few assumptions had to be made in order to follow with the analysis. This should not cause any irrevocable errors in the calculations as what it is presented in this thesis is three possible outcomes or possible paths for the decarbonization of the energy system. Considering the rate of emissions and predictions of future average global temperature, "the only possible path" is the B2DS, since it was designed to go even a little bit further than the Paris agreement objectives.

Some assumptions do represent big potential changes on findings. Like the case of thin-film technologies, which cause bottlenecks for many materials as indium, tellurium, gallium etc. The share of thin-film technologies is 20%, other values may lower or increase the supply bottleneck risk of this materials. The amount and type of vehicles per region was also estimated and can have a high impact on the overall consumption of some materials.

4 RESULTS

In this section the results of the materials quantification are presented. First it is shown how the total materials required are influenced by the type and quantity of technologies to be installed at a global scale. It is also shown how the demand for materials changes in all the regions considered and a comparison is made between total material requirements of each region and their respective annual productions, for each scenario. This last point is summarized in a table showing the materials with higher risk for each region. The second part of the results has to do with the estimated energy consumption for the extraction of the carrier metals (Al, Cu, Fe, Mn, Ni, Pb, Zn) according to the average ore grade of each.

4.1 Use of materials for low carbon energy technologies

This dissertation did not try to evaluate if low carbon technologies are more material intensive than fossil fuel technologies as this is already a known fact, due to the structure of the technologies itself and the need of more units than traditional energy technologies to produce the same amount of electricity. What is presented in this section instead is the total weight of materials required for the installation of low carbon electricity generation technologies, hybrid and electric vehicles and electricity storage with Li-on batteries as in the scenarios by the IEA. The results are firstly shown at a global scale as a cumulative line from 2014 till 2060. With this view it is possible to observe the different scale of the materials build-up and growth rate, as well as which are the most important materials to ensure the technology deployment in each scenario. Secondly is shown the total materials usage per low carbon technology according to the ETP scenarios from 2014 up to 2060, followed by the presentation of the demand for materials per region. Finally, it is assessed the most critical materials per region according to the required share of the regions annual production and reserves, in addition to the materials not produced.

4.1.1 Global material needs

In Table 15 it is possible to observe the impact that the different scenarios have in the total estimated demand of materials. It is also presented the growth of each material as the ambition of the scenario increases. The materials needed in higher quantities are Al, Fe and cement, which are materials common to most of the low carbon-technologies. Materials like Cd, Co, Cu, C, In, Li, Mg, Mn, Nb, Se, Ag, Te, Sn and show a two-fold increase between RTS and 2DS but have a smaller increase from the 2DS to B2DS. The exception to this are the materials used in batteries and electric vehicles (cobalt, graphite, lithium and manganese). Overall, there is a larger increase in materials' demand from RTS to 2DS (ranging between 35% for Ge to 1058% for Va) and a smaller increase from the 2DS to the B2DS (ranging between 0% for Ta to 99% for Ti)

Table 15 - Total material requirements from 2014 until 2060 according to the three scenarios. Growth comparision between the the three scenarios.

tonnes	RTS (a)	$\frac{b-a}{a}$	2DS (b)	$\frac{c-b}{b}$	B2DS (c)
Al	211,689,595	+69%	357,444,281	+40%	500,308,560
B	57,208	+69%	96,632	+55%	150,111
Cd	38,349	+120%	84,420	+5%	88,535
Cr	14,552,721	+82%	26,456,748	+4%	27,642,182
Co	2,717,202	+109%	5,669,169	+87%	10,573,380
Cu	31,549,467	+120%	69,483,989	+35%	93,489,260
Ga	5,283	+67%	8,800	+11%	9,780
Ge	53	+35%	72	+17%	85

tonnes	RTS (a)	$\frac{b-a}{a}$	2DS (b)	$\frac{c-b}{b}$	B2DS (c)
Au	241	+35%	326	+17%	381
C	18,770,750	+132%	43,567,999	+87%	81,578,799
In	11,612	+120%	25,529	+5%	26,780
Fe	2,003,475,764	+61%	3,228,037,178	+21%	3,921,276,440
Pb	22,111,138	+52%	33,502,064	+10%	36,838,006
Li	2,988,470	+131%	6,901,182	+97%	13,615,752
Mg	122,944	+119%	268,640	+5%	282,017
Mn	14,162,280	+142%	34,290,915	+70%	58,410,180
Mo	1,229,723	+85%	2,270,936	+3%	2,335,388
Ni	24,233,941	+96%	47,601,779	+37%	65,109,847
Nb	37,851	+161%	98,602	+17%	115,857
Pd	962	+35%	1,303	+17%	1,525
Se	13,972	+120%	30,771	+5%	32,269
Ag	59,936	+116%	129,196	+9%	140,192
Ta	6,632	+93%	12,791	+0%	12,837
Te	22,144	+120%	48,768	+5%	51,142
Sn	1,049,366	+120%	2,311,063	+5%	2,423,570
Ti	6,035,679	+136%	14,269,589	+99%	28,449,205
W	1,585	+97%	3,119	+6%	3,320
Va	6,910	+1058%	80,005	+23%	98,058
Zn	12,476,293	+65%	20,557,870	+5%	21,535,160
Zr	9,671	+97%	19,025	+6%	20,254
RE	2,432,966	+53%	3,712,427	+30%	4,835,459
Cement	1,987,428,102	+31%	2,593,719,753	+15%	2,984,412,775

In Figure 26 it is shown the cumulative values of the demand of materials according to the quantification made for the three scenarios (with the exception of aluminium, iron and cement due to the difference in the scale of values). There are eight materials that grow faster than the others in any of the scenarios: copper, nickel, lead, graphite, manganese, zinc, lithium and chromium. Copper is the backbone of our electricity system and although there are some possibilities of substitution they can only happen at the loss of efficiency or higher cost. Zinc and chromium are mainly used galvanizing and stainless steel. Nickel and manganese are also used to produce diverse alloys but have also a high use in the production of batteries for EVs or for electricity storage. To produce batteries there is also a great need for graphite and lithium. Although this are the materials which have a higher cumulative demand (after aluminium, iron and cement) that does not mean they are more critical. In order access their criticality, it is necessary to compare the annual amount required with the annual amount produced both at a global or regional scale.

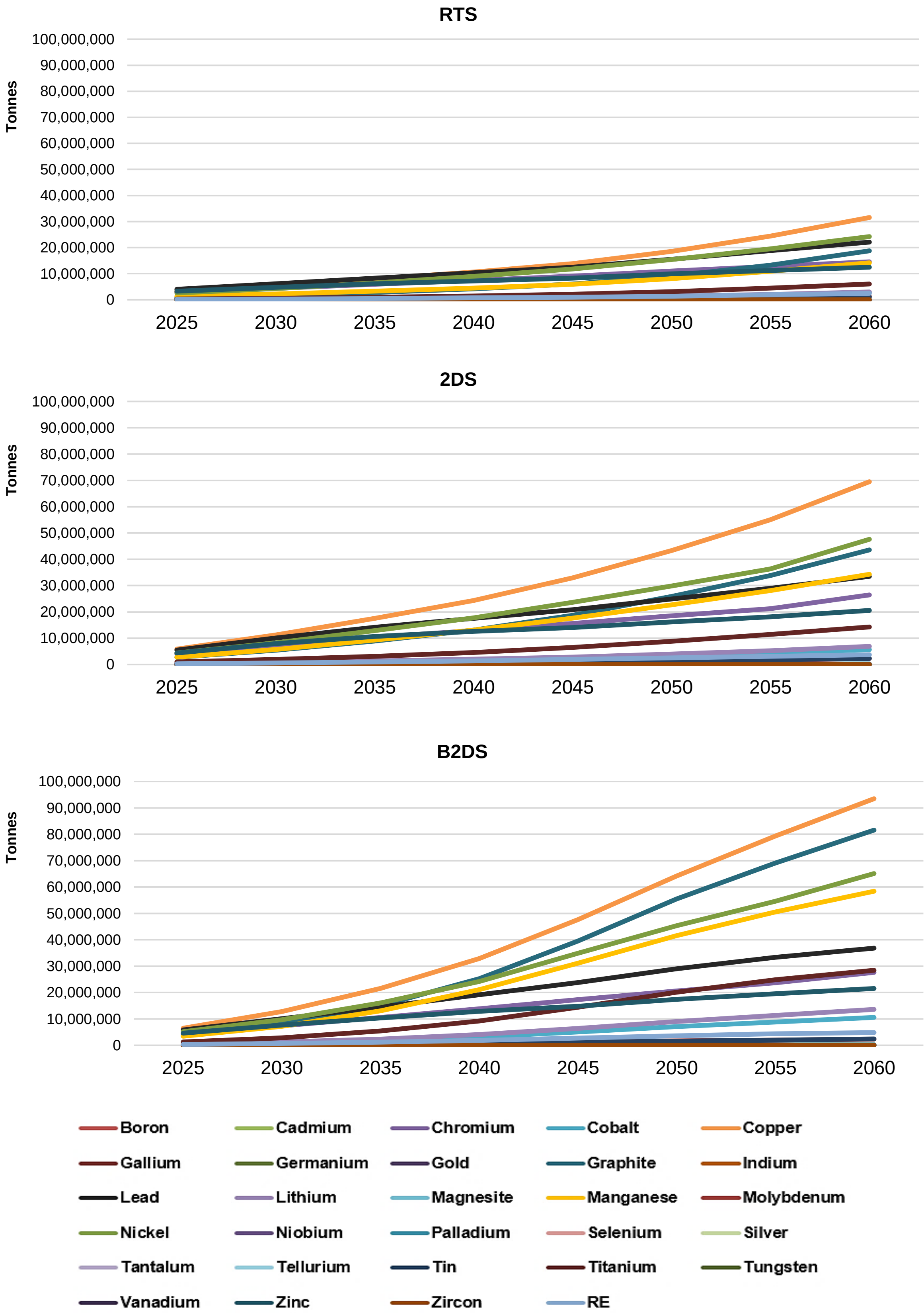


Figure 26 - Cumulative demand of materials up to 2060, for the three scenarios.

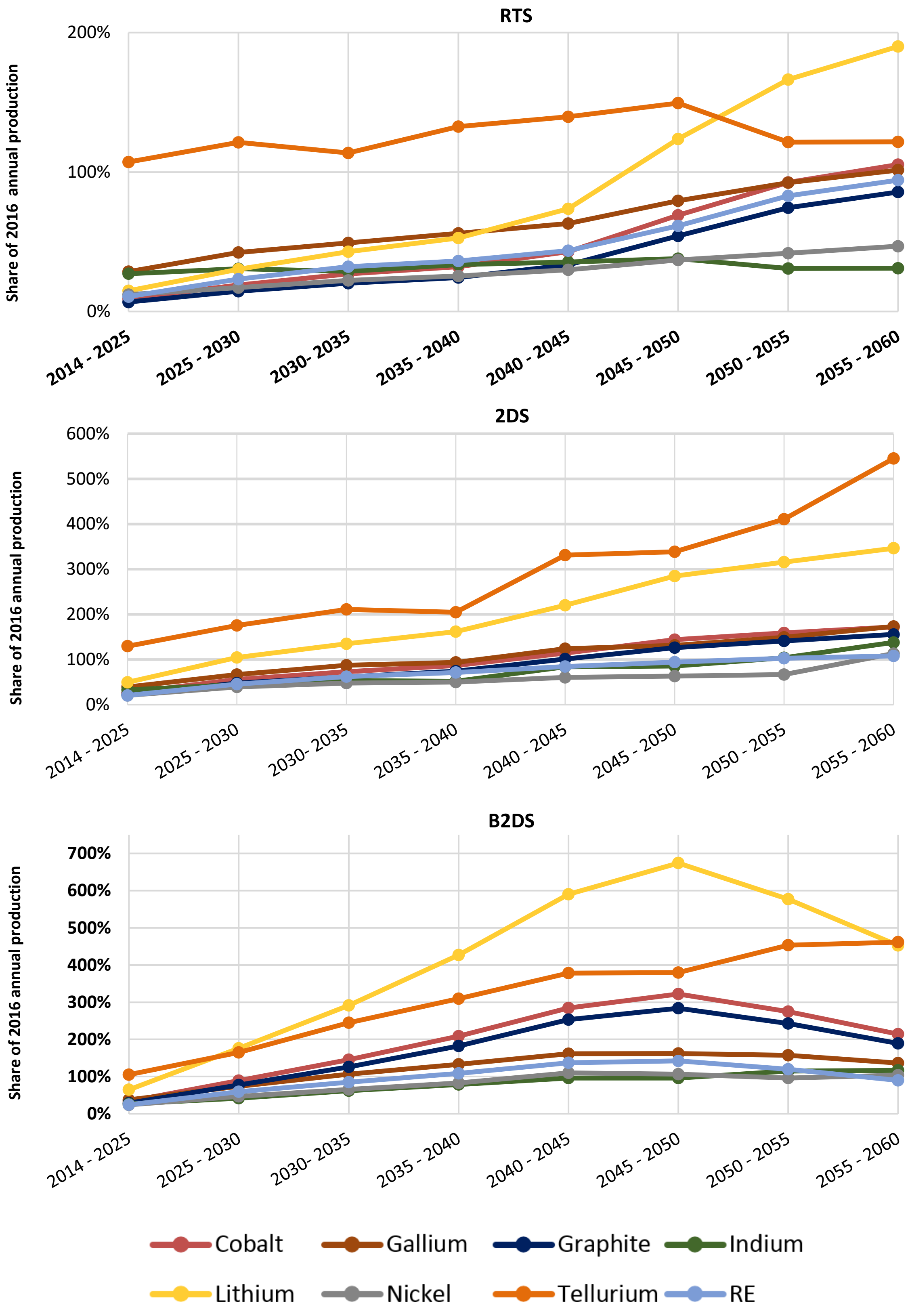
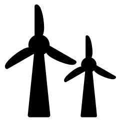


Figure 27 - Cumulative demand for materials according to the three scenarios, except for aluminium, iron and cement

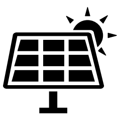
In the next tables it is possible to see the differences of demand of materials of each low-carbon technology in each of the ETP scenarios. Most rapid analysis shows that electric vehicles create most of the demand for most of the materials. Nickel, aluminium and copper are needed across most of the technologies.

Table 16 - Total demand of materials per low-carbon energy technology, according to each scenario up to 2060 (highlighted are the highest shares of each material)

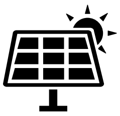


Wind Onshore	RTS (t)	% of total	2DS (t)	% of total	B2DS (t)	% of total
New Installed Capacity (GW)	2,070		3,035		3,136	
Al	3,280,922	2%	4,811,590	1%	4,971,481	1%
Concrete	977,998,452	10%	1,434,269,966	11%	1,481,931,470	10%
Cr	6,536,730	45%	9,586,350	36%	9,904,909	36%
Cu	3,772,999	12%	5,533,239	8%	5,717,111	6%
Fe	270,949,631	14%	397,357,395	12%	410,561,779	10%
Mn	2,464,882	17%	3,614,839	11%	3,734,962	6%
Mo	379,843	31%	557,054	25%	575,565	25%
Ni	1,548,667	6%	2,271,176	5%	2,346,648	4%
Pb	10,876,612	49%	15,950,944	48%	16,481,001	45%
Zn	10,659,287	85%	15,632,228	76%	16,151,695	75%
Notes: Cement was quantified as 20% of concrete						

Wind Offshore	RTS (t)	% of total	2DS (t)	% of total	B2DS (t)	% of total
New Installed Capacity (GW)	242		647		681	
Al	259,822	0%	693,643	0%	730,821	0%
Concrete	128,493,756	1%	343,037,938	3%	361,423,967	2%
Cr	163,767	1%	437,205	2%	460,638	2%
Cu	1,877,501	6%	5,012,338	7%	5,280,987	6%
Dy	2,847	1%	7,599	2%	8,007	2%
Fe	42,970,066	2%	114,716,569	4%	120,865,108	3%
Mn	288,505	2%	770,218	2%	811,500	1%
Mo	32,947	3%	87,958	4%	92,673	4%
Nd	21,803	2%	58,208	3%	61,328	2%
Ni	93,754	0%	250,294	1%	263,709	0%
Pb	1,273,067	6%	3,398,688	10%	3,580,850	10%
Pr	6,577	6%	17,559	10%	18,500	10%
Tb	1,696	8%	4,527	14%	4,770	13%
Zn	1,392,985	11%	3,718,831	18%	3,918,152	18%
Notes: 50% with PM; Cement was quantified as 20% of concrete						

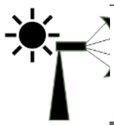


Solar PV	RTS (t)	% of total	2DS (t)	% of total	B2DS (t)	% of total
New Installed Capacity (GW)	2 823		6 216		6 519	



Solar PV	RTS (t)	% of total	2DS (t)	% of total	B2DS (t)	% of total
Ag	43,469	**73%**	95,733	**74%**	100,394	**72%**
Al	26,910,220	**13%**	59,265,631	**17%**	62,150,765	**12%**
Cd	38,190	**100%**	84,108	**100%**	88,203	**100%**
Cu	4,982,036	**16%**	10,972,170	**16%**	11,506,311	**12%**
Ga	1,942	**37%**	4,277	**49%**	4,485	**46%**
In	11,559	**100%**	25,456	**100%**	26,696	**100%**
Mg	120,809	**98%**	266,063	**99%**	279,016	**99%**
Pb	610,611	**3%**	1,344,777	**4%**	1,410,242	**4%**
Se	13,972	**100%**	30,771	**100%**	32,269	**100%**
Sn	1,049,362	**100%**	2,311,059	**100%**	2,423,565	**100%**
Te	22,144	**100%**	48,768	**100%**	51,142	**100%**
Zn	67,721	**1%**	149,145	**1%**	156,405	**1%**

Note: mix of 80% c-Si, 20% Thin Film



CSP	RTS (t)	% of total	2DS (t)	% of total	B2DS (t)	% of total
New Installed Capacity (GW)	**342**		**1 025**		**1 269**	
Ag	5,817	**10%**	17,430	**13%**	21,579	**15%**
Al	2,821,893	**1%**	8,455,488	**2%**	10,467,964	**2%**
Cement	55,091,923	**3%**	165,076,833	**6%**	204,366,468	**7%**
Cr	1,009,448	**7%**	3,024,700	**11%**	3,744,603	**14%**
Cu	765,641	**2%**	2,294,158	**3%**	2,840,186	**3%**
Fe	202,231,841	**10%**	605,965,270	**19%**	750,189,953	**19%**
Mn	1,317,416	**9%**	3,947,489	**12%**	4,887,024	**8%**
Mo	43,800	**4%**	131,241	**6%**	162,478	**7%**
Nb	23,953	**63%**	71,773	**73%**	88,855	**77%**
Ni	468,795	**2%**	1,404,691	**3%**	1,739,019	**3%**
Ti	4,277	**0%**	12,817	**0%**	15,867	**0%**
V	616	**9%**	1,846	**2%**	2,285	**2%**
Zn	350,741	**3%**	1,050,955	**5%**	1,301,091	**6%**

Hydropower	RTS (t)	% of total	2DS (t)	% of total	B2DS (t)	% of total
New Installed Capacity (GW)	**1 112**		**1 342**		**1 563**	
Concrete	**8,500,149,454**	**86%**	**10,259,749,317**	**79%**	**11,950,337,558**	**80%**
Cr	13,900	**0%**	16,777	**0%**	19,542	**0%**
Cu	76,172	**0%**	91,940	**0%**	107,090	**0%**
Fe	27,800,070	**1%**	33,554,910	**1%**	39,084,045	**1%**
Mg	2,135	**2%**	2,577	**1%**	3,002	**1%**
Mn	1,890	**0%**	2,282	**0%**	2,658	**0%**
Mo	3,225	**0%**	3,892	**0%**	4,534	**0%**

Hydropower	RTS (t)	% of total	2DS (t)	% of total	B2DS (t)	% of total
Ni	34,472	**0%**	41,608	**0%**	48,464	**0%**
Pb	5,960	**0%**	7,194	**0%**	8,380	**0%**
Sn	3	**0%**	4	**0%**	5	**0%**
Ti	267	**0%**	322	**0%**	375	**0%**
Zn	5,560	**0%**	6,711	**0%**	7,817	**0%**
Zr	0	**0%**	0	**0%**	0	**0%**
Notes: excluding pumped storage						

Ocean	RTS (t)	% of total	2DS (t)	% of total	B2DS (t)	% of total
New Installed Capacity (GW)	**45**		**279**		**335**	
Cr	14	**0%**	86	**0%**	104	**0%**
Cu	226	**0%**	1,394	**0%**	1,674	**0%**
Fe	2,036	**0%**	12,544	**0%**	15,064	**0%**
Mo	2	**0%**	14	**0%**	17	**0%**
Ni	10	**0%**	61	**0%**	74	**0%**
Ti	0	**0%**	3	**0%**	3	**0%**

Geothermal	RTS (t)	% of total	2DS (t)	% of total	B2DS (t)	% of total
New Installed Capacity (GW)	**104**		**200**		**201**	
Al	1,232,434	**1%**	2,377,068	**1%**	2,385,603	**0%**
Concrete	55,039,234	**1%**	106,157,378	**1%**	106,538,542	**1%**
Cr	6,673,667	**46%**	12,871,891	**49%**	12,918,108	**47%**
Cu	373,551	**1%**	720,490	**1%**	723,077	**1%**
Fe	27,089,593	**1%**	52,249,276	**2%**	52,436,880	**1%**
Mn	448,158	**1%**	864,388	**1%**	867,492	**1%**
Mo	746,999	**61%**	1,440,780	**63%**	1,445,954	**62%**
Nb	13,263	**35%**	25,582	**26%**	25,674	**22%**
Ni	12,450,501	**51%**	24,014,006	**50%**	24,100,230	**37%**
Ta	6,632	**100%**	12,791	**100%**	12,837	**100%**
Ti	169,316	**3%**	326,569	**2%**	327,741	**1%**
Notes: Cement was quantified as 20% of concrete						

Nuclear	RTS (t)	% of total	2DS (t)	% of total	B2DS (t)	% of total
New Installed Capacity (GW)	**317**		**624**		**664**	
Ag	2,632	**4%**	5,177	**4%**	5,512	**4%**
Cd	159	**0%**	312	**0%**	332	**0%**
Co	0	**0%**	0	**0%**	0	**0%**
Cr	135,296	**1%**	266,158	**1%**	283,357	**1%**
Cu	18,898	**0%**	37,176	**0%**	39,578	**0%**

Nuclear	RTS (t)	% of total	2DS (t)	% of total	B2DS (t)	% of total
In	507	4%	998	4%	1,063	4%
Mo	22,449	2%	44,162	2%	47,016	2%
Nb	634	2%	1,248	1%	1,328	1%
Ni	81,013	0%	159,371	0%	169,669	0%
Pb	1,363	0%	2,682	0%	2,855	0%
Ti	476	0%	936	0%	996	0%
V	190	3%	374	0%	398	0%
W	1,585	100%	3,119	100%	3,320	100%
Y	159	1%	312	1%	332	1%
Zr	9,671	100%	19,025	100%	20,254	100%

CCS	RTS (t)	% of total	2DS (t)	% of total	B2DS (t)	% of total
New Installed Capacity (GW)	61		778		954	
Co	458	0%	5,834	0%	7,153	0%
Cr	19,898	0%	253,580	1%	310,921	1%
Cu	42,238	0%	538,274	1%	659,991	1%
Mn	229,565	2%	2,925,504	9%	3,587,033	6%
Mo	458	0%	5,834	0%	7,153	0%
Nb	6,104	16%	77,785	79%	95,374	82%
Ni	69,889	0%	890,641	2%	1,092,037	2%
V	6,104	88%	77,785	97%	95,374	97%
Note: Includes Coal, Biomass and Natural Gas						

Electricity Storage	RTS (t)	% of total	2DS (t)	% of total	B2DS (t)	% of total
Al	659,541	0%	1,167,696	0%	1,940,888	0%
Co	287,248	11%	508,563	9%	845,308	8%
Cu	1,037,143	3%	1,836,228	3%	3,052,090	3%
C	1,369,329	7%	2,424,352	6%	4,029,642	5%
Fe	899,585	0	1,592,686	0%	2,647,286	0%
Li	383,795	13%	679,496	10%	1,129,426	8%
Mn	336,253	2%	595,324	2%	989,520	2%
Note: All electricity storage considered is Li-on batteries						

Hybrid & Electric Vehicles	RTS (t)	% of total	2DS (t)	% of total	B2DS (t)	% of total
Al	176,524,764	83%	280,673,166	79%	417,661,039	83%
B	57,208	100%	96,632	100%	150,111	100%
Co	2,429,497	89%	5,154,772	91%	9,720,919	92%
Cu	18,603,061	59%	42,446,582	61%	63,561,163	68%

Hybrid & Electric Vehicles	RTS (t)	% of total	2DS (t)	% of total	B2DS (t)	% of total
Dy	236,900		341,471		419,279	
Ga	3,341	63%	4,523	51%	5,295	54%
Ge	53	100%	72	100%	85	100%
Au	241	100%	326	100%	381	100%
C	17,401,421	93%	41,143,647	94%	77,549,157	95%
In	53	0%	72	0%	85	0%
Fe	1,431,532,942	71%	2,022,588,528	63%	2,545,476,325	65%
La	775,108	100%	1,049,356	100%	1,228,418	100%
Pb	9,343,524	42%	12,797,779	38%	15,354,678	42%
Li	2,604,675	87%	6,221,686	90%	12,486,326	92%
Mn	9,075,611	64%	21,570,870	63%	43,529,991	75%
Nd	1,241,660	98%	2,028,064	97%	2,889,293	
Ni	9,150,588	38%	17,974,606	38%	34,360,477	53%
Pd	962	100%	1,303	100%	1,525	100%
Pr	96,822	94%	161,352	90%	166,307	90%
Ag	8,018	13%	10,855	8%	12,708	9%
Tb	20,046	92%	27,139	86%	31,769	87%
Ti	5,861,344	97%	13,928,943	98%	28,104,222	99%
Note: Includes materials for HEV, PHEV, BEV						

It is perceptible that EV's have very high material requirements which alone puts a lot of pressure on the supply of some materials, not only used in batteries and electric system for the vehicle, but also the structure. These materials get even more critical when following the B2DS which considers a majority of BEV by 2060. Electricity generation technologies create all the demand for Cd, Cr, In, Mg, Mo, Nb, Se, Ta, Te, Sn, W, Va, Zn and Zr. Geothermal energy is very consuming of Cr, Mo, Ni, and Ta, CSP requires a big share of Nb and Hydropower almost all the concrete quantified. Nuclear energy requires W as a radiation shield. In terms of the two largest electricity producing technologies of the future, solar and wind, they create high demand for materials like Cr, Pb and Zn for wind energy and Ag, Cd, In, Mg, Nb, Se, Te and Sn. Figure 28 resumes the relative weight that each considered group of low-carbon technologies has on the total demand of materials. It is noticeable that electricity storage batteries will have a trivial impact in terms of total material demand. It is noticeable that electricity storage will have a trivial impact in terms of total material demand.

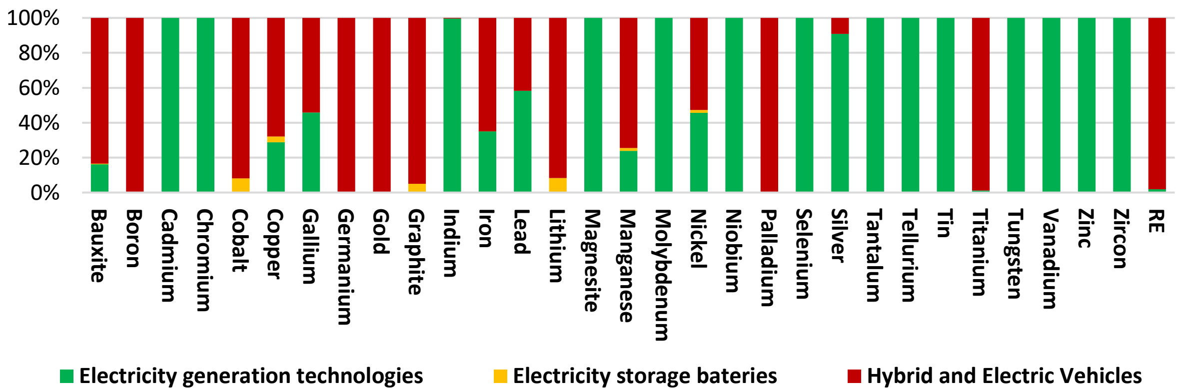


Figure 28 - Share of total material requirements per technology in 2060

It was chosen to present only one scenario because in terms of share of total demand there is not much difference between scenarios. In terms of absolute values there are significant differences in the total values as it can be seen in the previous tables.

4.1.2 Materials needs per region

In this sub-section it is presented the material consumption per region of the world. All the values will be presented here as a share of the world total demand according to the three scenarios. Absolut values can be found in the annexes. It can be observed in Figure 29 that the regions considered in this study represent an average of more than 90% of the global demand of materials. China plus USA represent an average around 40% while India plus the EU an average around 20% of the global demand of materials, in any given scenario. The main differences between RTS and 2DS is the increased share that India has of global demand. It is also worth noticing that Brazil although being the main producer of Niobium in the world, is the region with the smallest share of total demand of this material USA and China show similar requirements except for W and Zr, two materials used in nuclear energy.

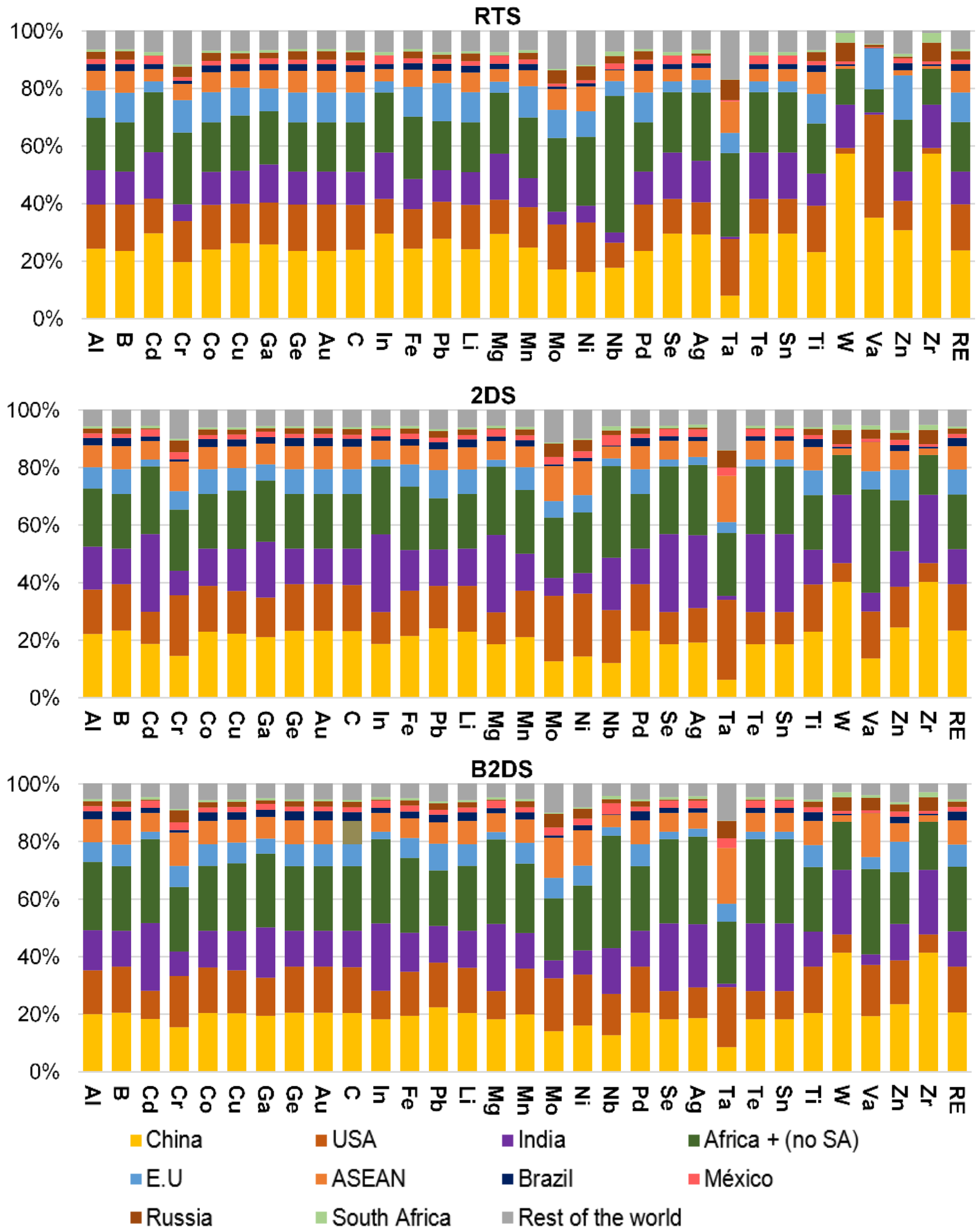


Figure 29 - Share of global requirements of each mineral per region in 2060 according to each scenario

4.2 Assessing potential materials supply bottlenecks for deployment of low carbon technologies.

In this section the annual needs of materials for each scenario are compared with the annual production of each region and the estimated reserves. This will enable to identify the most critical materials per region by identifying the materials required but not produced and the materials which need to increase production in order to meet the estimated demand. This analysis is done at a global scale (world, OCDE, non-OCDE) and regionally for the 10 regions.

4.2.1 Assessing material dependency per region

By aggregating the rare earths into only one category, this study considers a total of 31 materials essential to the energy transition to a low carbon energy system. In this sub-section an assessment is made of the most critical materials for the world, OECD and Non-OECD and for the ten regions. A comparison is made between the materials extracted annually in each region and the average annual requirements according to the three ETP scenarios. The materials are categorized as they represent over 50, 75, 100 or 500%.

In Table 17 it´s presented the number of materials which are not produced in each of the regions. All the regions but China and Russia have problems with the variety of metals they produce (not considering OECD and Non-OECD groups). The regions which present a bigger need of imports due to the fact that they produce a relatively small variety of minerals necessary are: Mexico which doesn't produce 19 of the 31 minerals, South Africa (16), India (15), USA (16) and ASEAN (12).

Table 17 – Materials not produced in each region

Regions	Nº NP	Materials not extracted in the region
China	1 /31	Pd;
Africa +	2 /31	Te, RE;
Russia	3 /31	C, Li, Mn;
Brazil	7 /31	B, Ga, Ge, Mo, Pd, Se, Te;
EU	9 /31	B, Ge, Mo, Nb, Ta, Ti, Va, Zr, RE;
ASEAN	12 /31	B, Cd, Ga, Ge, C, In, Li, Mo, Nb, Pd, Te, Va;
USA	13 /31	Cr, Ga, C, In, Mg, Mn, Nb, Se, Ta, Sn, W, Va, RE;
India	15 /31	B, Co, Ga, Ge, In, Li, Mo, Ni, Nb, Pd, Ta, Te, W, Va, RE;
South Africa	16 /31	Al, B, Cd, Ga, Ge, C, In, Li, Mo, Nb, Se, Ta, Te, Sn, W, RE;
México	19 /31	Al, B, Cr, Co, Ga, Ge, In, Li, Ni, Nb, Pd, Ta, Te, Sn, Ti, W Va, Zr, RE;

In Table 18, Table 19 and Table 20. the materials required are categorized by the share of the regions annual production they require annually. In the RTS, the least ambitious scenario, problems arise at the global scale for Tellurium, which in average requires, annually until 2060, more than 100% of the world annual production in 2016. Less problematic but also a risk case is lithium, which requires more than 75% in the same terms. It can also be observed that the OECD has a worst position than the Non-OECD, since it has a bigger demand than production for five minerals.

Other alarming signs come from China, where the annual production of Co, Ni, Li and Nb in 2016 seems insufficient for the average annual requirements of this scenario up to 2060. India, a country which may grow its electricity consumption by more than 400% in any of the scenarios, appears to not to have enough annual production to meet even the least ambitious scenario (RTS) in terms of Cu, Cd and Se. This is specially concerning since in this dissertation, the electricity transmission and distribution lines (T&D) weren´t considered (due to lack of data) and it is predictable that it will create a very high demand for copper.

Overall, the RTS is the least ambitious scenario and represents a path that is not enough to accomplish the Paris agreement scenarios or slow down global warming and still it shows a demand for materials that is concerning for various regions. These results are presented as percentages in the annexes 5,6,7.

Table 18 - Minerals categorized by percentage of the average annual requirements of the regions annual production in 2016, for the RTS until 2060

RTS	World	OECD	Non-OECD	ASEAN	EU	Brazil	China	India	México	Russia	S. A	USA	Africa +
≥50%	Ga	Te Sn		Fe		RE	Te			Ga RE		Ti	
≥75%	Li					In Ag				Co			C Li Se
Count	**2**	**2**	**0**	**1**	**0**	**3**	**1**	**0**	**0**	**3**	**0**	**1**	**3**
≥100%	Te	Co Ga C Ta RE	Li Te	Cr Co Pb Ta	Co Ga Mn Ni Sn	Co Pb Li	Co Li Ni Nb	Cd Cu Se		Fe Ta		Ni Te	Ga
Count	**1**	**5**	**2**	**4**	**5**	**3**	**4**	**3**	**0**	**2**	**0**	**2**	**1**
≥500%				RE	C Li Pd		Cr	Sn	Fe			Al Co Li	In
Count	**0**	**0**	**0**	**1**	**3**	**0**	**1**	**1**	**1**	**0**	**0**	**3**	**1**

For the 2DS a lot more materials have more demand than supply as it can be seen in Table 19. Globally, in the RTS only Te showed a total lack of production while in this scenario Co, Ga and Li also present a need to increase its production. Li is also a big concern for the EU, Brazil and USA where it shows an average annual need of more than 500% of the regions annual production until 2060, while globally, in average, is required annually over 75% of the annual production of 2016. Five of the 10 regions require more than 100% of the regions annual production of Co and the USA requires more than 500% of this material.

Table 19 - Minerals categorized by percentage of the average annual requiremnents of the regions annual production in 2016, for the 2DS until 2060

2DS	World	OECD	Non-OECD	ASEAN	EU	Brazil	China	India	México	Russia	S. A	USA	Africa +
≥50%	In Ni RE		RE C	Se Ti Zn	Te			Au Pb		Ga RE	Ag	Cd	Ni
≥75%	C	Li Ni	Co Ga In	Fe Ag			Te			Mo	Co		Nb
Count	**4**	**2**	**5**	**5**	**1**	**0**	**1**	**2**	**0**	**3**	**2**	**1**	**2**
≥100%	Co Ga Li Te	Co Ta Te Sn RE	Li Te	Co Pb	Co Ga Mn Ni	Co In Pb Ag Re	Co Li Ni	C Ag	C	Co Ta		Te Ti	Ga C Li Se
Count	**4**	**5**	**2**	**2**	**4**	**5**	**3**	**2**	**1**	**2**	**0**	**2**	**4**
≥500%		Ga C		Cr Ta RE	C Li Pd Sn	Li	Cr Nb	Cd Cu Se Sn	Fe	Fe		Al Co Li Ni	In
Count	**0**	**2**	**0**	**3**	**4**	**1**	**2**	**4**	**1**	**1**	**0**	**4**	**1**

The B2D is presented by the IEA as the scenario that needs to be followed in order to keep the average world temperature increase by 1,75ºC considering the pre-industrial era. Looking at Table 20 it is possible to observe that even at a global scale, there is a need to increase the production of at least 8 of the 31 materials, not even considering the use of this materials in other applications. In this scenario BEV's will be the main vehicle on the road from 2030 forward. This creates a high demand for Li which is why, not only there's a higher need than production in the whole world, as there is a need of over 500% for 5 of the 10 regions (EU Brazil, China, USA, Africa +). The same happens with Co and graphite also used in batteries. The most mediatic material concerning supply risks are the rare earth (RE) elements, but in this work, although they present a high level of the world 2016 annual production (over 75%), they show supply risks in only two of the ten regions (ASEAN and Brazil). This may be due to the share of offshore wind turbines considered (50%) or due to the electric vehicles in the 2DS are in majority PHEV which make smaller use of RE.

Table 20 - Minerals categorized by percentage of the average annual requiremnents of the regions annual production in 2016, for the B2DS until 2060

B2DS	World	OECD	Non-OECD	ASEAN	EU	Brazil	China	India	México	Russia	S. A	USA	Africa +
≥50%			Se Ni	Se Zn	Sn		C	Au Pb		Ga RE	Ag	Cd Fe	Co Ni
≥75%	In Ni RE		Ga In RE	Ag		C	Te			Mo			
Count	**3**	**0**	**5**	**3**	**1**	**1**	**2**	**2**	**0**	**3**	**1**	**2**	**2**
≥100%	Co Ga C Li Te	Li Ni Ta Te Sn RE	Co C Te	Co Fe Pb Ti	Ga Ni	In Pb Ag RE	Co Ni	C Ag	C	Co Ta	Co	Te Ti	C Nb Se
Count	**5**	**6**	**3**	**4**	**2**	**4**	**2**	**2**	**1**	**2**	**1**	**2**	**3**
≥500%		Co Ga C	Li	Cr Ta RE	Co C Li Mn Pd Sn	Co Li	Cr Li Nb	Cd Cu Se Sn	Fe	Fe		Al Co Li Ni	Ga In Li
Count	**0**	**3**	**1**	**3**	**6**	**2**	**3**	**4**	**1**	**1**	**0**	**4**	**3**

Considering this aspect, the countries that already have a small diversity across production show even more dependence on imports due to lack of annual production.

The EU is an example of a region which present a good variety of metals it mines (22 in 31 totals) but has a small annual production of some which even in the least ambitious scenario creates supply risks for an additional 8 of the 31 minerals. cobalt, gallium and natural graphite are the most critical minerals for the OECD countries, while for the Non-OECD is Li, since Australia and Chile (the largest producers of Li) belong to the first group.

The need of this materials for other applications is not considered and was out of this dissertation aim. Still this is a very important factor, which can determine the share of the annual production that already has a market and that might be difficult to substitute.

It cannot be forgotten that supply from secondary production is also not being considered in this quantification. Although this no doubt this factor could lower the amount of virgin materials required from each region primary production, it was not the aim of this dissertation. Some materials that are needed in vast quantities (such as aluminium, copper, iron, zinc, lead, nickel, tin) have recycling rates over 50% and some close to 100%. But there other materials which for now do not have a stable recycling industry and so many present values under 1% (UNEP 2011).

The use of materials in other applications and the recycling rate by balance somewhat. This means that as recycling can lower the amount of primary production required, the use of the same materials in other applications may also create a lower availability of materials to be used in the low carbon technologies.

Table 21 - Number of materials not produced in the region plus number of materials which require 100% or more of the known reserves for the total required until 2060; (In bold are the materials that also show problems with the annual production)

>100% RESERVES	RTS	2DS	B2DS
World	-	Te	Te
OECD	**Al**, Co, **Pd**, Te	**Al**, Co, **Pd,** Te	**Al**, Co Ni, **Pd**, Te
Non-OECD	-	Te	Co, Li, Te
ASEAN	-	Co	Co, **Ti**
EU	**Te**, Li	Pb, **Te**, Li	Pb, **Te**, Li
Brazil	Li	Li	Li
China	**Mn**, Ni, **Te**	**Mn**, Ni, **Te**	**Mn**, Ni, **Te**
India	**Pb**	**Pb**	C, **Pb**
México	-	-	-
Russia	-	-	-
South Africa	-	-	-
USA	Cr, Ni, Co, Li	Co, Cr, **Mo**, Ni, **Pd**, Te, Li	Co, Cr, **Mo**, Ni, **Pd**, Te, Li
Africa +	-	-	Li

In Table 21 it can be observed the required share of each region’s reserves compared with the estimates of total material demand until 2060. Some materials that did not present problems in terms of required annual production now show a lack of reserves (highlighted in bold). The data for the reserves comes from the USGS, the only source available worldwide. This data are estimates and are not presented for all countries which produce them. For the materials that already presented concerns with the annual production rate, also present problems with the level of reserves at the regional level. Only tellurium does not present enough reserves for the entire world in the 2DS and B2DS, which can only be solved by either reducing the market share of CdTe solar panels or by finding materials that can substitute it, preferably without the loss of efficiency. Observing Figure 30 there is a clearer picture of the regions and materials which are more critical.

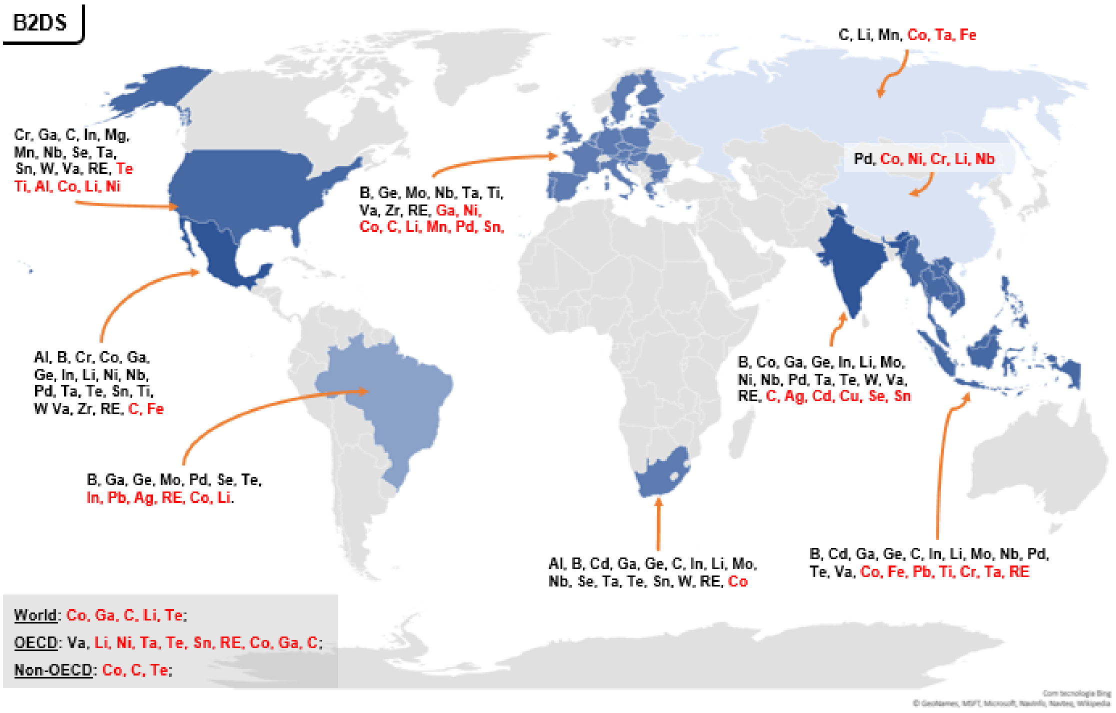


Figure 30 - Materials most critical for each region, including those not produced and those which require an average of 100% or more of the annual production in 2016 (in red)

China, Russia and Brazil are the regions better positioned for the energy transition. On the other side India, USA and Mexico are the worst positioned due to the number of materials not produced.

4.2.2 Material flows for low-carbon energy technologies

It was the initial objective of this dissertation to analyse the exchanges between regions of the 31 materials considered. In Figure 31 it is presented simple charts of the 8 materials most critical for the B2DS, comparing the sum of annual productions of each region in 2016 with the average annual needs of materials of each region. There are other countries that produce this material which are not part of the 10 regions considered, meaning that a production smaller than the required consumption showed in the chart does not necessarily mean that there is not enough supply globally, as it was presented in the previous tables.

Cobalt is required in amounts that exceed the production. It is clear that the Africa+ region is the main source of this material (D.R Congo produced in 2016 55% of global cobalt), but still the annual production of the 10 regions is about half of the required for the same. D.R. Congo is not considered a stable government which might create some issues in the future is no substitute material is found, and also there is the issue of using child labour in the mines.

Gallium has a slightly higher needs by the 10 regions than the annual production of the same. This material is required for thin-film solar PV and electric vehicles. China clearly controls the global production of this material (88%) and might be the main supplier of the other regions.

Graphite is another important material used in Li-ion batteries which presents annual needs above annual production, among the 10 regions. China is once again the main producer (69% of global production) with only a few other regions also producing it. China also has the highest needs for this material and is the only region that produces enough to supply itself.

Indium has a chart similar to gallium, with China responsible for 63% of global production. It presents needs among the 10 regions that are slightly higher than the production.

Lithium is one of the most concerning materials because it is used in many different technologies besides EV batteries or stationary storage batteries. It presents one of the highest differences between needs and production, although the two main producers globally (Chile and Australia) are not part of the 10 regions. These two regions, which belong to the OCDE can control the global market of this material, which are not the worst news since both seem to have stable governments.

Nickel is required by a broad number of low-carbon technologies as well as other technologies. ASEAN is the global main producer, followed by Russia and Africa+. These three regions will have no problem self-supplying it and will be the main suppliers in the future.

Tellurium has its only use in low-carbon technologies for producing thin-film solar PV panels (CdTe). This material shows lack of production globally and also a lack of reserves. So, this type of technologies will most likely not be able to be a part of the transition to a low-carbon energy system, at least at a great scale and if there are no new deposits found.

Rare Earth elements include Dy, Nd, and Pr which are vital materials for the production of permanent magnets used in gearless wind turbines and electric vehicles. The needs of this materials far surpasses the production and is mainly extracted in China which is responsible for 84% of global production. This is one of the most mediatic materials because of its importance for more efficient and less maintenance motors. If no substitute is found for this material, there will be a demand higher than supply which might cause the prices to go up.

The charts for all the materials considered can be found in the annexes 13,14 and 15, according to each scenario.

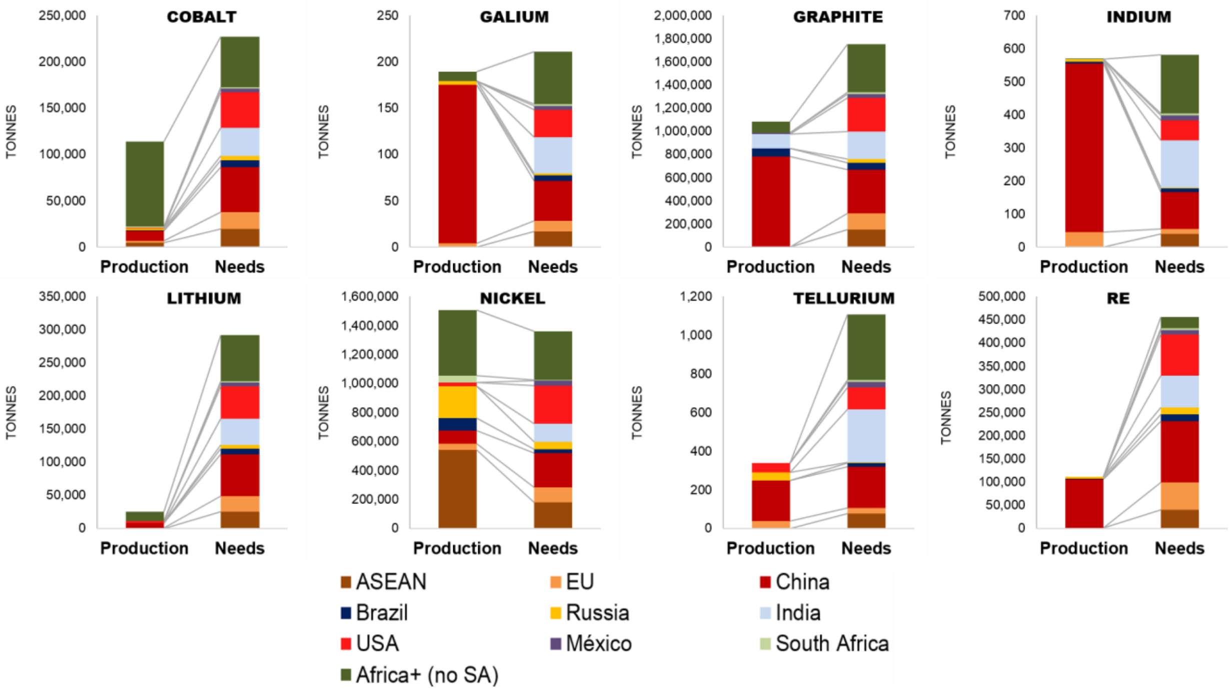


Figure 31 - Most critical materials. Comparision between 2016 annual production and average annual requirements according to the B2DS.

On Table 22 the estimated time of bottleneck occurrence is shown for the three scenarios. Tellurium, as seen before, is the most critical material and its bottleneck is estimated to happen during the first-time gap.

Table 22 - Estimated time gaps for the ocurrence of bottlenecks, according to each scenario.

Time frame for material bottleneck	RTS	2DS	B2DS
Co	2055-2060	2040-2045	2030 - 2035
Ga	2055-2060	2040-2045	2030 - 2035
C	NA	2040-2045	2030 - 2035
In	NA	2050-2055	2050 - 2055
Li	2045-2050	2025-2030	2025 - 2030
Ni	NA	2055-2060	2040 - 2045
Te	2014-2025	2014-2025	2014 - 2025
Re	N/A	2050-2055	2035 - 2040

Supply bottleneck existences according to the B2DS are estimated to happen mostly around the decade of 2030, with the exception of indium which is estimated to happen later and tellurium which is expected to happen sometime during the next 20 years.

4.2.3 Overall valuation

The average results for 7 indicators studied show that India is the country which shows the least capacity to follow any of the plans, considering resources and capacity. USA comes second on the worst performers, it has bad results in the availability of many of the 31 required materials either because it is not mined in the country or because the mining rate is not sufficient. There is also the problem of the currently estimated reserves which is where the USA has the worst position, although this may change rapidly when a new deposit is found, it takes around 10 years to build a viable operational mine.

Table 23 - Summary of the performance of the various regions, according to the three scenarios and seven indicators.

Average of the 3 scenarios	ASEAN	EU	Brazil	China	India	Mexico	Russia	S. A	USA	Africa+
Nº of materials NP	2	1	1	0	2	3	0	3	2	0
Nº of materials > 100%	2	2	3	2	2	0	1	0	1	2
Nº materials > 500%	2	3	1	1	2	1	0	0	3	1
Nº Reserves >100%	0	1	1	2	1	0	0	0	3	0
Growth installed capacity	2	0	1	1	3	1	0	0	0	1
Growth electricity demand	2	0	1	1	3	1	0	0	0	2
Average global demand of each material	1	1	0	3	2	0	0	0	2	3

Average Score		TOTAL	Comments
1º	Russia	2.9	Some materials may need extra recycling or increase production to meet the specific B2DS scenarios until 2060.
2º	S. Africa	3.7	Small diversity of materials largely mined. It enables S. Africa an advantage in trade.
3º	Brazil	6.7	Moderate growth of low carbon technologies. Some materials need to increase production. Largest share renewables in 2014 and 2060.
4º	México	7.1	It requires many materials which does not produce but in smaller quantities.
5º	EU	9.2	Small annual production for the existent demand, even though it mines most materials.
6º	Africa+	9.2	Africa + represents a big group of countries and so a large demand of materials was expected. All indicators point to self-sufficiency.
7º	China	9.2	It has an average demand for materials comparable only with Africa +. The remain indicators follow Africa + with the exception of number of reserves which China has worse grade.
8º	ASEAN	10.7	This region as issues with most of the indicators, specially the number of materials not produced and the annual productions of the ones it does.
9º	USA	11.4	The number of materials NP, the size of reserves and annual production are the main problems for this region
10º	India	14.3	India has the highest growth of installed capacity and electricity demand. It produces few of the required materials and has problems with annual of production.

India has the right to increase the access to electricity of its population, but it is also expected to grow the population itself at a high rate. This puts India in the worst position, and if the growth of electricity demand and installed capacity were not a factor, would be positioned around the middle of the table above, even though it shows a lack of production of many materials.

USA is the world largest economy, but still presents a lack of production and reserves which might cause several issues, especially considering the recent trade wars imposed by Donald Trump.

ASEAN is close to the world main producers of most materials like China, Russia and Australia and is the world largest producer of nickel which might give it an advantage in trade. Nonetheless it is possible that electricity demand will rise and should be obtained from renewable sources, which will require large amounts of materials which it does not seem to have.

Africa + and China got the same score mainly because of the average global demand they require, still Africa + got a little better score due to having larger reserves than China, although it may need to grow electricity demand a lot more than China.

The EU will need higher production than it currently has in order to meet the material demand quantified. The remaining regions do present some supply bottlenecks but require smaller amounts of the materials since they are not expected to grow the electricity demand or the installed capacity as much as the other regions.

4.3 Energy consumption from resource mining for low carbon energy technologies deployment

All the values until now for the required weight of materials for low carbon technologies as well as for the annual production values were as metal content which means it was after the smelting and refining phases.

The values here presented consider only the extraction and concentration phases which are composed of several other stages as it can be seen in Figure 32 by (Norgate and Haque 2010). In this case the stages are for the extraction and concentration of copper in an underground mine. The fact that it is an underground mine is the reason for the high value for ventilation. What it can be concluded is that crushing, and grinding is the phase which is responsible for the largest share of emissions due to high energy consumption.

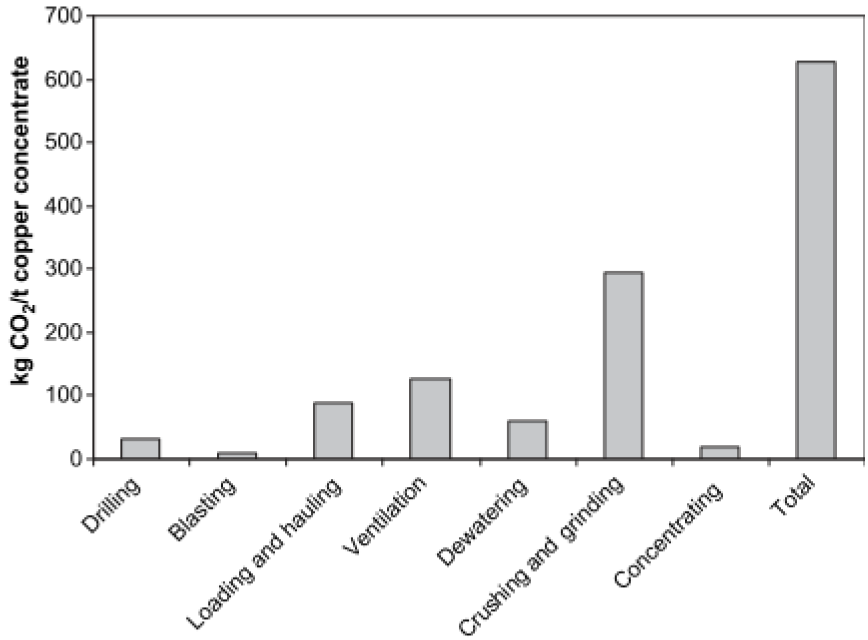


Figure 32 - Stage contributions to GWP for copper concentrate production. Retrieved from (Norgate and Haque 2010)

Considering the average global ore grade of the carrier metals and the total material requirements for the energy transition and using the energy consumption factors presented by (Norgate and Haque 2010) it was calculated the total energy consumption as seen it can be seen in Table 24.

Table 24 - Total world energy consumption for extraction of all required materials until 2060, according to the B2DS

Material	Ore grade (t metal/t ore)	2014-2060 Requirements (t)	Ore (t)	Electricity (PJ)	Diesel (PJ)	Total (PJ)
Al	0.3	500,308,560	1,667,695,200	3	11	63,372
Cu	0.0059	93,489,260	15,845,637,288	735	2,647	1,822,248
Fe	0.5	3,921,276,440	7,842,552,880	24	85	694,412
Mn	0.48	151,811,432	316,273,817	1	3	30,062
Ni	0.012	65,109,847	5,425,820,583	16	59	515,724
Pb	0.0044	36,838,006	8,372,274,091	25	90	795,785
Zn	0.05	21,535,160	430,703,200	1	5	40,938

Figure 33 shows the share that each material has of the total energy consumption. Cu, Ni and Pb are responsible for a large share of the total energy consumption mainly due to the low ore grades they present. Fe is required in quantities much larger than any other material, but it also has the highest ore grade.

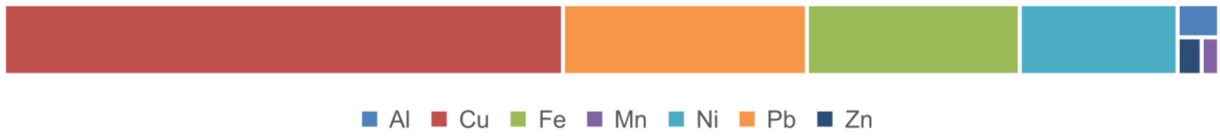


Figure 33 -Total PJ from extraction of carrier minerals considering average global ore grade, according to B2DS until 2060

It is also worth noticing that recycling is a lot less energy intensive than extracting and refining virgin material. In this dissertation recycling wasn´t considered and all of this carrier metals have very high rates of recycling. Table 25 shows the theoretically share that each region is responsible due to the material consumption they require to make the energy transition to a low carbon energy system.

Table 25 - Total energy consumption per region according to each scenario

PJ	ASEAN	EU	Brazil	China	India	Mexico	Russia	South Africa	USA	Africa + (no SA)	TOTAL PJ
RTS	95,597	183,601	38,094	426,504	177,485	26,874	38,964	13,938	234,613	331,678	**1,567,348**
	6%	**12%**	**2%**	**27%**	**11%**	**2%**	**2%**	**1%**	**15%**	**21%**	
2DS	286,373	240,642	66,730	650,071	400,385	63,389	82,078	23,430	573,055	695,440	**3,081,594**
	9%	**8%**	**2%**	**21%**	**13%**	**2%**	**3%**	**1%**	**19%**	**23%**	
B2DS	408,064	320,203	105,865	848,857	534,465	90,476	104,227	31,593	716,456	1,062,146	**4,222,352**
	10%	**8%**	**3%**	**20%**	**13%**	**2%**	**2%**	**1%**	**17%**	**25%**	

The ore grade has been diminishing in the last years and well as the distance to the surface. This means it is required much larger amount of energy to extract and concentrate which also means a higher levels of emissions and toxic leaching from tailings. (Norgate and Haque 2010) In Figure 34 it is possible to understand the effects of the ore grade on the overall energy consumption of a copper mine.

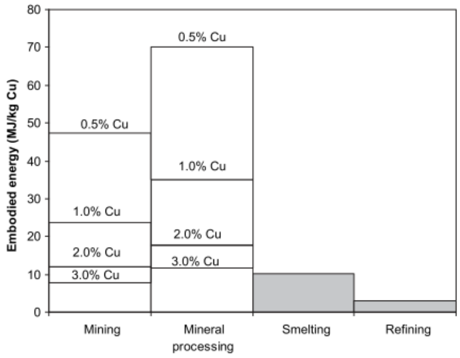


Figure 34 - Effect of ore grade on embodied energy for pyrometallurgical copper production. Image retrieved from (Norgate and Haque 2010);

The energy consumption as well as the envrironmental impacts are very difficult to quantify, since each mine has its own specifications. Still further research should be done considering these factors.

5 CONCLUSIONS

There is no doubt that the challenge the world faces of transitioning from a fossil fuel-based economy to a low carbon energy system is a task of enormous proportions, especially if the advices from the scientific community concerning limiting the average temperature increase of our planet are to be followed. The IEA created three scenarios (RTS, 2DS, B2DS) for the transition to a low carbon energy system, with the limit year of 2060, which differentiate themselves by the potential impact they can have on the increase of the future global average temperature. In this dissertation it was assessed the amount of materials (a total of 31 materials were analysed) required to follow each of the scenarios, having into account the most recent data of the annual production of each them, at the global and regional level (for a total of 10 regions).

The efforts and commitments being made by the governments around the world since the Paris agreement are a step toward this transition, but if the rate of burning fossil fuels continues as estimated in the International's Energy Agency (IEA) Reference Technology Scenario (RTS), the world has little chance of achieving the goals of reducing the temperature increase to well under 2ºC until de end of the century. The 2-Degrees Scenario (2DS) can take us closer to the required transition but still with only a 50% chance, so the estimated best option is to follow the path traced by the B2DS. To do this with no obstacles its required that all the materials are readily available in a comfortable quantity in order to not create shortages or spikes in the price due to times of superior demand than supply.

5.1 Energy transition in the world – Supply & Demand

The three scenarios present three levels of ambition for the degree of energy transition to a low carbon energy system. But, according with the IEA, only the B2DS was forecasted do accomplish the Paris agreement and reducing or not worsening the climate change impacts. These scenarios require that very large amounts of new renewable installed capacity needs to be installed in the next four decades. As it was seen with wind onshore there might be a need of a global addition of approximately [2,000-3,000] GW, for solar PV it´s between [2,800 – 6,519] GW till 2060 comparing that with total installed capacity in 2017 (solar: 400 GW and wind: 515 GW) there is still a lot to do.

Data on the 2016 annual production of each material was collected for the globe and for each of the 10 regions. The scenarios created by the EIA provided data of the situation of the globe and each region for the base year of 2014, in terms of the installed capacity and type of the electricity production and electricity storage technologies and also stocks and types of vehicles. Each scenario as also data for each five years in to the future up to 2060. By crossing this data, it was possible to assess the regions at most risk of not producing enough of the required materials, according to each scenario, as well as the ones which have more than enough. A final evaluation was completed by comparing the score that each region got for seven indicators created, which have into account the number of materials not produced but required, the number of materials produced but not in enough quantities, the share of reserves required, the average global demand of each material and also the growth in installed capacity and electricity demand.

The analysis showed that the richest countries are the poorest in resources. This could be seen by comparing the number of materials for which the OECD countries presents bottlenecks (9 in 31) and the Non-OECD (4 in 31) according with the B2DS scenario. India, which by growing its economy will increase the access to electricity to a great number of people currently not connected to the grid, is expected to grow the demand for electricity by around 400% in any of the scenarios and does not seem to present enough variety and/or quantity of materials to meet the requirements for self-sufficiency being then one of the most material dependant region of all considered. The needs for materials in the poorest countries is aggravated by the fact is that, like India, they require the largest increase in electricity access due to their expected economy and population growth.

There is a need to improve the collection and recycling of materials which means embracing a circular economy. Goverments around the world have a key importance in facilitating this transition by introducing new policies and financing operations. There is the need to invest in scientific research in order to keep improving the efficiency, cost and safety of the low carbon technologies existent today, and also to find new ways of producing electricity with renewable sources, of storing energy and of low carbon mobility. It is also very important to keep increasing the number of materials with high recicability and to increase the recicability of the materials used not only in electricity generation technologies but all the gadgets present in society nowadays which compete in use.

Based on the findings of this dissertation, overall there is the high probability that most of the nations of this world will go from a fossil fuel dependency to a mineral / metal dependency of the exterior. Until now no other scientific study is found about the regional materials requirements for the energy transition to a low carbon energy system. The studies analysed in Table 1 have mostly come to the same conclusions in terms of the most critical materials for the world. In this dissertation eight materials were considered the most critical (Co, Ga, C, In, Li, Ni, Te, Re). Of these eight materials, nickel was the only material not marked as critical by any of the studies in Table 1. Gallium, indium and tellurium were appointed by most as critical materials, as well as diverse rare earth elements, which in this study were aggregated in only one category. The materials chosen as critical have of course to do with the scenarios/model used, the electricity generation technologies and respective material use factor considered. As well as if recyclability was considered or any other socio-economic factors.

There is no doubt the world must follow the path traced by the B2DS, a similar one or one even a more ambitious one in order to successfully mitigate (and be capable of adapting) to climate change. The research questions of this dissertation ask if this is possible considering that renewable technologies are more material intensive than conventional fossil fuel burning plants. After analysing the data and results at global level there are some causes for concern, but this could be mitigated by changing the technologies used, by improving the material use efficiency, by increasing recycling or substitute materials.

Therefore, at the global level, with some changes specially in terms of the share of solar thin-film technologies, it is possible to follow the B2DS path. This conclusion is in line with the conclusions of most of the studies on this subject. At the regional scale however, there are many areas of the planet that require materials that they do not have. This material deficiency can be solved either by implementing the same mitigation actions that are required at a global scale or by maintaining a healthy trade with the regions that have more than enough for its on necessities. What will happen ca not be predicted but this dissertation highlights some of the possible implications for materials needs for low-carbon energy transition in the different regions of our planet.

5.2 Limitations of the analysis and future developments

This dissertation can serve as a base for a thorough future analysis where the gaps and assumptions made here can be better tuned to make an even more realistic material consumption scenario.

The assumptions here made were caused by the fact that some of data probably used by IEA in the ETP 2017 is not freely accessible to the public. This data includes specifications of the sub-technologies considered, data per country / continent or the remaining regions not present in ETP 2017, data on the stock of hybrid and electric vehicles per region, data of the electricity storage capacity per region. For all of the previous it was necessary to make assumptions on regional distribution.

As future developments it is suggested that a better look is taken at the impact that recycling can have on this quantification, as well as the options for substitution of some materials. The demand from other applications is also essential to make a complete assessment of the demand of materials.

Electricity storage is essential for a low carbon energy system. The main way of currently storing electricity is with pumped hydropower. Li-Ion batteries for electricity storage are important specially at a smaller scale for home installed solar PV. Most probably batteries for large scale stationary storage for industry will not be made out of lithium. Many new batteries are being designed which will be able to store more energy and survive more cycles, but the best commercially available battery nowadays are from Li-Ion family. Batteries for EV's are different from batteries for stationary electricity storage as they need to provide different functions. EV batteries need to have both high power (for acceleration) and high energy capacity (autonomy) while stationary batteries require mostly high energy capacity. (Science for Environment Policy 2018)

Li-Ion batteries have very low recyclability nowadays due to the number of blended materials as well as different chemical compositions for the electrode. Spent Li-ion batteries should not be landfilled or incinerated due to the risk of explosion and leaching of toxic substances they present. Spent EV batteries are a pressing concern and require a correct end of life treatment. The options available for this type of battery are eco-design, standardization of formats and materials or re-use spent EV batteries in less demanding stationary applications.(Science for Environment Policy 2018)

There was an initial idea of creating a matrix for the most likely necessary exchanges of materials between regions and evaluate the environmental impacts of the transport. Unfortunately, this was not possible in this study as that represents enough work to create a second dissertation. It is than suggested that this analysis is realized in the future.

It was not possible to analyse the demand for all the technologies and structures needed for the transition to a low carbon energy system. One of the most important of those are the electricity transmission and distribution (T&D) lines which is believed by the authors to have a major impact on the demand of certain materials, such as copper, iron, lead and aluminium. There are many variables to have into account in doing this quantification as the length of the required cables is dependent on the type of technology used (HVDC or HVAC) which in turn each has different materials necessary, different T&D losses, different infrastructures needed etc. Is also needing to have knowledge of which part of the new T&D will be submarine, underground or overhead, and the amount of current installed T&D that needs to be substituted by new.

A closer look must be taken into the environmental impacts of the mining industry, specially related to solid and liquid emissions that happen on a daily basis and also the impacts of noise, explosions, machinery movement and deforestation on the local wildlife.

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7 ANNEXES

Annex 1- Comparison of total material requirements for each scenario and the respectevely share of world annual production and reserves

	RTS			2DS			B2DS		
Scenario Comparison	t	% annual production	% Reserves	t	% annual production	% Reserves	t	% annual production	% Reserves
Bauxite	211,689,595	1.8%	1%	357,444,281	3%	1%	500,308,560	4%	2%
Boron	57,208	0.0%	0%	96,632	0%	0%	150,111	0%	0%
Cadmium ①	38,349	3.3%	NA	84,420	8%	NA	88,535	8%	NA
Chromium	14,552,721	2.5%	3%	26,456,748	5%	5%	27,642,182	5%	5%
Cobalt	2,717,202	49.7%	38%	5,669,169	104%	80%	10,573,380	196%	149%
Copper	31,549,467	3.6%	4%	69,483,989	8%	9%	93,489,260	11%	12%
Dysprosium (RE)	239,746	0.0%	0%	349,071	0%	0%	427,286	0%	0%
Gallium ②	5,283	64.0%	NA	8,800	108%	NA	9,780	121%	NA
Germanium ③	53	1.1%	NA	72	1%	NA	85	2%	NA
Gold	241	0.2%	0%	326	0%	1%	381	0%	1%
Graphite	18,770,750	39.2%	7%	43,567,999	91%	16%	81,578,799	173%	30%
Indium ④	11,612	31.9%	NA	25,529	74%	NA	26,780	79%	NA
Iron	2,003,475,764	3.0%	2%	3,228,037,178	5%	4%	3,921,276,440	6%	5%
Lanthanum (RE)	775,108	0.0%	1%	1,049,356	0%	1%	1,228,418	0%	1%
Lead	22,111,138	10.6%	25%	33,502,064	16%	38%	36,838,006	18%	42%
Lithium	2,988,470	86.8%	19%	6,901,182	202%	43%	13,615,752	407%	85%
Magnesite	122,944	0.0%	0%	268,640	0%	0%	282,017	0%	0%
Manganese	64,520,513	2.2%	9%	128,937,511	5%	19%	151,811,432	9%	22%
Neodymium (RE)	1,263,464	0.0%	1%	2,086,271	0%	2%	2,950,620	0%	2%
Molybdenum	1,229,723	9.9%	7%	2,270,936	19%	13%	2,335,388	19%	14%
Nickel	24,233,941	29.0%	33%	47,601,779	58%	64%	65,109,847	79%	88%
Niobium	37,851	1.0%	1%	98,602	3%	2%	115,857	3%	3%
Palladium ⑤	962	11.1%	1%	1,303	15%	2%	1,525	17%	2%
Praseodymium (RE)	103,400	0.0%	0%	19,510,984	0%	16%	20,228,159	0%	17%
Samarium (RE)	29,507	0.0%	0%	17,152	0%	0%	7,787	0%	0%
Selenium	13,972	9.2%	14%	30,771	21%	31%	32,269	23%	32%
Silver	59,936	5.0%	11%	129,196	11%	24%	140,192	12%	26%
Tantalum	6,632	9.1%	6%	12,791	18%	12%	12,837	18%	12%
Tellurium	22,144	125.9%	71%	48,768	293%	157%	51,142	312%	165%
Terbium (RE)	21,742	0.0%	0%	31,666	0%	0%	36,539	0%	0%
Tin	611,974	6.8%	13%	1,347,459	16%	28%	1,413,098	17%	29%
Titanium	6,035,679	2.1%	1%	14,269,589	5%	2%	28,449,205	10%	3%
Tungsten	1,585	0.0%	0%	3,119	0%	0%	3,320	0%	0%
Vanadium	6,910	0.2%	0%	80,005	2%	0%	98,058	3%	0%
Zinc	12,476,293	2.1%	5%	20,557,870	4%	9%	21,535,160	4%	9%
Zircon	9,671	0.0%	0%	19,025	0%	0%	20,254	0%	0%
RE	2,432,966	48.0%	12.2%	23,044,500	73%	19%	24,878,810	96%	21%

Annex 2 - Material requirements for all regions until 2060 according with the RTS (in kilotons)

Kt	ASEAN	EU	Brazil	China	India	México	Russia	South Africa	USA	Africa +
Al	14,614	20,099	4,849	51,536	25,275	3,545	5,458	1,665	32,360	40,188
B	4	6	1	13	7	1	2	0	9	10
Cd	2	1	1	11	6	1	0	0	5	8
Cr	828	1,631	161	2,865	853	182	527	104	2,070	3,730
Co	189	284	65	653	309	42	75	21	422	489
Cu	1,806	3,078	755	8,281	3,606	541	643	267	4,337	6,309
Ga	0	0	0	1	1	0	0	0	1	1
Ge	0	0	0	0	0	0	0	0	0	0
Au	0	0	0	0	0	0	0	0	0	0
C	1,333	1,961	450	4,492	2,143	286	538	140	2,941	3,362
In	0	0	0	3	2	0	0	0	1	3
Fe	119,097	207,811	45,715	488,250	210,357	32,418	47,846	18,080	274,503	451,673
Pb	944	2,918	547	6,137	2,446	356	356	193	2,839	3,947
Li	204	314	71	722	339	47	81	23	461	539
Mg	5	5	2	36	20	4	0	1	15	27
Mn	784	1,540	303	3,497	1,433	227	329	127	1,994	3,106
Mo	88	121	11	210	55	12	57	7	192	321
Ni	2,071	2,161	273	3,937	1,394	250	1,181	110	4,172	5,923
Nb	1	2	0	7	1	1	1	1	3	19
Pd	0	0	0	0	0	0	0	0	0	0
Se	1	1	0	4	2	0	0	0	2	3
Ag	2	3	1	18	9	2	0	1	7	15
Ta	1	0	0	1	0	0	0	0	1	2
Te	1	1	0	7	4	1	0	0	3	5
Sn	45	40	19	311	169	30	1	12	126	231
Ti	457	619	141	1,399	675	87	191	42	972	1,093
W	0	0	0	1	0	0	0	0	0	0
Va	0	1	0	2	0	0	0	0	2	1
Zn	220	1,921	316	3,837	1,279	209	73	127	1,265	2,369
Zr	0	0	0	6	1	0	1	0	0	2
RE	182	250	60	579	278	36	72	17	388	435

Annex 3 - Material requirements for all regions until 2060 according with the 2DS (in kilotons)

Kt	ASEAN	EU	Brazil	China	India	México	Russia	South Africa	USA	Africa +
Al	27,090	26,618	9,126	79,367	53,501	5,772	6,132	2,603	54,895	74,595
B	8	8	3	23	12	1	2	1	16	19
Cd	5	2	1	16	23	2	0	1	9	21
Cr	2,725	1,683	213	3,857	2,261	658	1,076	151	5,558	5,773
Co	438	484	156	1,303	730	82	111	39	903	1,118
Cu	5,232	5,380	1,700	15,457	10,154	1,192	1,202	547	10,335	14,644
Ga	1	0	0	2	2	0	0	0	1	2
Ge	0	0	0	0	0	0	0	0	0	0
Au	0	0	0	0	0	0	0	0	0	0
C	3,402	3,745	1,218	10,082	5,510	614	870	295	6,966	8,566
In	2	1	0	5	7	1	0	0	3	6
Fe	210,081	248,107	73,139	692,101	458,411	61,801	57,492	29,179	506,694	740,896
Pb	2,431	3,291	806	8,081	4,213	520	769	246	4,955	6,211
Li	530	589	190	1,585	893	101	135	48	1,097	1,360
Mg	17	6	4	50	72	7	1	2	30	66
Mn	2,494	2,715	736	7,242	4,418	589	709	302	5,497	7,885
Mo	277	129	15	288	141	58	105	10	516	486
Ni	5,592	2,870	584	6,813	3,404	1,064	1,894	208	10,396	10,248
Nb	4	3	0	12	18	4	2	1	18	33
Pd	0	0	0	0	0	0	0	0	0	0
Se	2	1	0	6	8	1	0	0	3	8
Ag	7	4	2	25	33	3	1	1	15	33
Ta	2	0	0	1	0	0	1	0	4	3
Te	3	1	1	9	13	1	0	0	5	12
Sn	149	56	37	431	625	57	8	21	257	566
Ti	1,163	1,220	398	3,275	1,717	197	304	92	2,339	2,809
W	0	0	0	1	1	0	0	0	0	0
Va	8	5	0	11	5	1	3	1	13	30
Zn	1,343	2,186	429	5,025	2,544	361	504	173	2,896	3,810
Zr	0	0	0	8	5	0	1	0	1	3
RE	300	322	106	867	451	51	73	25	596	732

Annex 4 - Material requirements for all regions until 2060 according with the B2DS (in kilotons)

Kt	ASEAN	EU	Brazil	China	India	México	Russia	South Africa	USA	Africa +
Al	39,922	34,288	14,187	100,384	69,530	8,939	8,469	3,729	76,099	122,252
B	13	11	5	31	19	2	3	1	24	35
Cd	6	2	2	16	21	2	0	1	9	27
Cr	3,188	2,029	252	4,287	2,363	738	1,141	145	4,897	6,336
Co	854	797	316	2,157	1,348	177	197	77	1,671	2,464
Cu	7,376	6,741	2,531	19,024	12,785	1,717	1,603	723	13,933	22,662
Ga	1	1	0	2	2	0	0	0	1	3
Ge	0	0	0	0	0	0	0	0	0	0
Au	0	0	0	0	0	0	0	0	0	0
C	6,666	6,173	2,468	16,696	10,278	1,347	1,546	588	12,951	18,948
In	2	1	0	5	6	1	0	0	3	8
Fe	265,243	271,094	95,628	763,624	534,008	81,437	66,839	33,036	597,413	1,052,673
Pb	2,730	3,434	989	8,249	4,692	597	846	271	5,730	7,364
Li	1,097	1,028	406	2,778	1,737	229	254	99	2,149	3,172
Mg	19	7	5	52	66	7	1	2	27	85
Mn	4,719	4,189	1,485	11,663	7,215	1,045	1,194	457	9,245	14,597
Mo	327	167	17	328	145	65	110	9	431	511
Ni	7,939	4,539	1,148	10,456	5,473	1,495	2,285	331	11,498	15,029
Nb	5	3	0	15	18	4	2	1	17	47
Pd	0	0	0	0	0	0	0	0	0	0
Se	2	1	1	6	8	1	0	0	3	10
Ag	8	4	2	26	31	4	1	1	15	44
Ta	2	1	0	1	0	0	1	0	3	3
Te	3	1	1	9	12	1	0	0	5	15
Sn	159	62	43	443	570	61	8	21	238	729
Ti	2,407	2,154	867	5,809	3,481	464	564	201	4,570	6,579
W	0	0	0	1	1	0	0	0	0	1
Va	15	4	0	19	4	1	4	1	17	30
Zn	1,379	2,279	499	5,055	2,727	371	546	171	3,289	4,036
Zr	0	0	0	8	5	0	1	0	1	4
RE	407	369	149	995	593	78	90	35	774	1,120

Annex 5 - Material requirements as percentage of regions annual production, for the RTS.

RTS	**World**	**OECD**	**Non-OECD**	ASEAN	EU	Brazil	China	India	Mexico	Russia	S. A	USA	Africa+
Al	2%	2%	2%	4%	24%	0%	2%	2%	NP	2%	NP	785%	2%
B	0%	0%	0%	NP	NP	NP	0%	NP	NP	0%	NP	13%	0%
Cd	3%	1%	5%	NP	2%	8%	3%	401%	2%	0%	NP	33%	5%
Cr	2%	8%	2%	185%	7%	1%	505%	1%	NP	7%	0%	NP	1%
Co	49%	138%	36%	102%	273%	176%	136%	NP	NP	82%	40%	1445%	12%
Cu	4%	2%	5%	4%	7%	5%	10%	269%	2%	2%	9%	19%	2%
Ga	64%	409%	46%	NP	243%	NP	18%	NP	NP	59%	NP	NP	250%
Ge	1%	9%	1%	NP	NP	NP	0%	NP	NP	1%	NP	7%	24%
Au	0%	0%	0%	0%	29%	0%	0%	43%	0%	0%	0%	0%	0%
C	39%	271%	27%	NP	6861%	15%	13%	41%	46%	NP	NP	NP	81%
In	32%	19%	37%	NP	20%	94%	15%	NP	NP	3%	NP	NP	12273%
Fe	3%	2%	3%	54%	26%	0%	3%	4%	14227%	435%	1%	37%	5%
Pb	11%	13%	10%	101%	34%	133%	6%	39%	3%	4%	11%	29%	12%
Li	85%	41%	196%	NP	2199%	252%	209%	NP	NP	NP	NP	523%	85%
Mg	0%	0%	0%	2%	0%	0%	0%	0%	0%	0%	0%	NP	0%
Mn	2%	4%	2%	4%	189%	1%	4%	4%	3%	NP	0%	NP	1%
Mo	10%	10%	10%	NP	NP	NP	4%	NP	2%	42%	NP	23%	19%
Ni	30%	43%	25%	9%	121%	8%	108%	NP	NP	13%	6%	396%	29%
Nb	1%	3%	1%	NP	NP	0%	402%	NP	NP	4%	NP	NP	43%
Pd	11%	22%	9%	NP	7915%	NP	NP	NP	NP	1%	0%	29%	5%
Se	9%	3%	20%	16%	1%	NP	12%	301%	7%	0%	NP	NP	85%
Ag	5%	2%	7%	25%	3%	93%	11%	43%	1%	1%	32%	24%	4%
Ta	9%	110%	5%	206%	NP	0%	11%	NP	NP	139%	NP	NP	3%
Te	126%	73%	149%	NP	43%	NP	68%	NP	NP	1%	NP	110%	NP
Sn	7%	71%	5%	1%	385%	2%	7%	42693%	NP	3%	NP	NP	11%
Ti	2%	2%	2%	21%	NP	7%	3%	5%	NP	3%	0%	56%	1%
W	0%	0%	0%	0%	0%	0%	0%	NP	NP	0%	NP	NP	0%
Va	0%	NP	0%	NP	NP	0%	0%	NP	NP	0%	0%	NP	0%
Zn	2%	2%	2%	9%	6%	4%	2%	4%	1%	1%	10%	15%	2%
Zr	0%	0%	0%	0%	NP	0%	0%	0%	NP	0%	0%	13%	0%
RE	48%	146%	36%	759%	NP	69%	13%	NP	NP	55%	NP	NP	NP

Annex 6 - Material requirements as percentage of regions annual production for the 2DS.

2DS	**World**	**OECD**	**Non-OECD**	ASEAN	EU	Brazil	China	India	México	Russia	S. A	USA	Africa +
Al	3%	3%	3%	8%	32%	1%	3%	5%	NP	2%	NP	1302%	3%
B	0%	0%	0%	NP	NP	NP	0%	NP	NP	0%	NP	0%	0%
Cd	8%	3%	12%	NP	3%	16%	4%	1571%	4%	1%	NP	53%	12%
Cr	5%	16%	3%	612%	8%	2%	667%	3%	NP	14%	0%	NP	1%
Co	102%	266%	79%	233%	470%	436%	279%	NP	NP	116%	78%	2978%	28%
Cu	8%	5%	11%	12%	13%	12%	19%	771%	4%	4%	19%	17%	6%
Ga	108%	583%	84%	NP	284%	NP	25%	NP	NP	60%	NP	NP	478%
Ge	1%	11%	1%	NP	NP	NP	0%	NP	NP	1%	NP	9%	35%
Au	0%	0%	0%	1%	32%	0%	0%	62%	0%	0%	0%	1%	0%
C	90%	582%	65%	NP	13188%	41%	30%	105%	100%	NP	NP	NP	211%
In	74%	39%	90%	NP	29%	194%	20%	NP	NP	32%	NP	NP	30704%
Fe	5%	4%	6%	95%	31%	1%	5%	9%	27167%	524%	2%	46%	8%
Pb	16%	19%	15%	261%	39%	207%	8%	67%	5%	10%	14%	33%	18%
Li	200%	87%	479%	NP	4211%	694%	476%	NP	NP	NP	NP	1190%	221%
Mg	0%	0%	0%	7%	0%	0%	0%	1%	0%	0%	0%	NP	0%
Mn	5%	10%	4%	12%	338%	2%	8%	13%	7%	NP	0%	NP	2%
Mo	19%	21%	18%	NP	NP	NP	5%	NP	11%	77%	NP	34%	29%
Ni	59%	88%	49%	24%	159%	17%	184%	NP	NP	20%	11%	1050%	51%
Nb	3%	11%	2%	NP	NP	0%	702%	NP	NP	6%	NP	NP	75%
Pd	15%	28%	12%	NP	8803%	NP	NP	NP	NP	1%	0%	39%	7%
Se	21%	6%	50%	54%	2%	NP	16%	1180%	15%	1%	NP	NP	213%
Ag	11%	5%	16%	75%	4%	184%	16%	171%	1%	1%	57%	31%	8%
Ta	18%	244%	10%	586%	NP	0%	16%	NP	NP	221%	NP	NP	5%
Te	293%	149%	364%	NP	64%	NP	95%	NP	NP	11%	NP	247%	NP
Sn	16%	144%	13%	2%	573%	5%	10%	167342%	NP	32%	NP	NP	28%
Ti	5%	5%	5%	52%	NP	21%	7%	13%	NP	5%	0%	102%	2%
W	0%	0%	0%	0%	0%	0%	0%	NP	NP	0%	NP	NP	0%
Va	2%	NP	2%	NP	NP	0%	1%	NP	NP	0%	0%	NP	5%
Zn	4%	4%	3%	60%	6%	6%	2%	8%	1%	4%	14%	8%	3%
Zr	0%	0%	0%	0%	NP	0%	0%	1%	NP	0%	0%	0%	0%
RE	73%	207%	57%	1277%	NP	123%	20%	NP	NP	55%	NP	NP	NP

Annex 7 - Material requirements as percentage of regions annual production for the B2DS.

B2DS	**World**	**OECD**	**Non-OECD**	ASEAN	EU	Brazil	China	India	Mexico	Russia	S. A	USA	Africa +
Al	4%	4%	4%	11%	41%	1%	4%	7%	NP	3%	NP	1832%	6%
B	0%	0%	0%	NP	NP	NP	0%	NP	NP	0%	NP	0%	0%
Cd	8%	3%	12%	NP	3%	19%	4%	1471%	4%	1%	NP	53%	15%
Cr	5%	15%	3%	724%	9%	2%	748%	3%	NP	15%	0%	NP	2%
Co	196%	493%	156%	462%	796%	895%	476%	NP	NP	216%	162%	5687%	63%
Cu	11%	6%	16%	17%	16%	18%	24%	991%	5%	5%	26%	23%	9%
Ga	121%	624%	95%	NP	293%	NP	25%	NP	NP	65%	NP	NP	634%
Ge	2%	12%	1%	NP	NP	NP	0%	NP	NP	1%	NP	11%	49%
Au	0%	0%	0%	1%	33%	0%	0%	73%	0%	0%	0%	1%	0%
C	173%	1071%	127%	NP	22183%	84%	50%	201%	226%	NP	NP	NP	474%
In	79%	38%	98%	NP	33%	227%	21%	NP	NP	31%	NP	NP	39356%
Fe	6%	4%	7%	121%	34%	1%	5%	10%	35871%	610%	2%	54%	12%
Pb	18%	21%	17%	293%	41%	257%	8%	74%	6%	10%	15%	39%	22%
Li	407%	171%	992%	NP	7552%	1511%	859%	NP	NP	NP	NP	2405%	527%
Mg	0%	0%	0%	7%	0%	0%	0%	1%	0%	0%	0%	NP	0%
Mn	9%	16%	8%	23%	532%	3%	13%	22%	12%	NP	0%	NP	4%
Mo	19%	19%	19%	NP	NP	NP	6%	NP	12%	81%	NP	28%	30%
Ni	79%	103%	71%	35%	246%	33%	275%	NP	NP	24%	16%	1138%	73%
Nb	3%	11%	2%	NP	NP	0%	869%	NP	NP	6%	NP	NP	106%
Pd	17%	31%	15%	NP	8922%	NP	NP	NP	NP	1%	0%	45%	10%
Se	23%	6%	54%	56%	2%	NP	17%	1104%	17%	1%	NP	NP	273%
Ag	12%	5%	17%	80%	5%	216%	17%	164%	2%	1%	57%	32%	11%
Ta	18%	212%	11%	721%	NP	0%	23%	NP	NP	231%	NP	NP	5%
Te	312%	145%	394%	NP	71%	NP	98%	NP	NP	10%	NP	245%	NP
Sn	17%	141%	14%	2%	641%	5%	10%	156670%	NP	31%	NP	NP	36%
Ti	10%	10%	10%	108%	NP	45%	12%	27%	NP	9%	0%	202%	6%
W	0%	0%	0%	0%	0%	0%	0%	NP	NP	0%	NP	NP	0%
Va	3%	NP	2%	NP	NP	0%	1%	NP	NP	1%	0%	NP	5%
Zn	4%	4%	4%	62%	7%	7%	2%	8%	1%	5%	14%	9%	3%
Zr	0%	0%	0%	0%	NP	0%	0%	1%	NP	0%	0%	0%	0%
RE	96%	260%	75%	1727%	NP	171%	23%	NP	NP	68%	NP	NP	NP

Annex 8 - Material requirements as percentage of regions reserves according to the RTS

RTS	World	OECD	Non-OECD	ASEAN	EU	Brazil	China	India	México	Russia	South Africa	USA	Africa +
Al	1%	343%	0%	0%		0%	5%	3%		1%			0%
B	0%	0%	0%				0%			0%		23%	0%
Cd													
Cr	3%	21%	2%					2%			0%	334%	1%
Co	38%	194%	27%	67%							8%	1837%	8%
Cu	4%	3%	5%	7%			31%		1%			10%	2%
Ga													
Ge													
Au	0%	1%	0%	1%		0%	3%		0%	0%	0%		0%
C	7%	6%	8%			1%	8%	27%	9%				12%
In													
Fe	2%	2%	2%		9%	0%	7%	4%			2%	36%	1%
Pb	25%	18%	32%		265%		36%	111%	6%	6%			20%
Li	19%	10%	34%		523%	149%	23%					1317%	22%
Mg	0%	0%	0%		0%	0%	0%	0%		0%			0%
Mn	2%	5%	2%			0%	7285%	4%	5%		0%		1%
Mo	7%	22%	5%				3%		9%	6%		192%	6%
Ni	33%	43%	28%	22%		2%	136%			16%	3%	3209%	29%
Nb	1%	4%	1%			0%							
Pd	1%	272%	1%							1%	0%	172%	0%
Se	14%	16%	13%		18%		16%			0%		17%	9%
Ag	11%	8%	12%		3%		45%		4%	1%			5%
Ta	6%	4%	12%			0%							
Te	71%	99%	63%		126%		99%					76%	25%
Sn	22%	48%	18%	3%		3%	28%			0%			28%
Ti	1%	1%	1%	29%		0%	1%	1%			0%	3%	1%
W	0%	0%	0%	0%	0%		0%			0%	2690%		0%
Va	0%		0%				0%			0%	0%		0%
Zn	5%	5%	6%		51%		9%	12%	1%				3%
Zr	0%	0%	0%				1%	0%			0%		0%
RE	2%	17%	1%	1%		0%	1%			0%		28%	5%

Annex 9 - Material requirements as percentage of regions reserves according to the 2DS

2DS	World	OECD	Non-OECD	ASEAN	EU	Brazil	China	India	México	Russia	South Africa	USA	Africa +
Al	1%	530%	1%	1%		0%	8%	6%		1%			0%
B	0%	0%	0%				0%			0%		39%	0%
Cd													
Cr	5%	40%	3%					4%			0%	896%	1%
Co	80%	377%	58%	156%							14%	3925%	18%
Cu	9%	6%	11%	20%			57%		3%			23%	4%
Ga													
Ge													
Au	1%	1%	1%	1%		0%	4%		0%	0%	0%		0%
C	16%	13%	19%			2%	18%	69%	20%				32%
In													
Fe	4%	4%	4%		11%	1%	10%	9%			4%	67%	2%
Pb	38%	26%	50%		299%		48%	191%	9%	12%			31%
Li	43%	21%	82%		982%	395%	50%					3133%	55%
Mg	0%	0%	0%		0%	0%	0%	0%		0%			0%
Mn	5%	11%	4%			1%	15088%	13%	12%		0%		2%
Mo	13%	44%	9%				3%		45%	11%		516%	9%
Ni	64%	87%	55%	60%		5%	235%			25%	6%	7997%	50%
Nb	2%	14%	2%			0%							
Pd	2%	343%	1%							1%	0%	235%	0%
Se	31%	31%	30%		25%		22%			1%		34%	22%
Ag	24%	17%	27%		4%		64%		9%	1%			12%
Ta	12%	8%	21%			0%							
Te	157%	187%	147%		175%		138%					155%	61%
Sn	48%	90%	42%	11%		5%	39%			2%			69%
Ti	2%	1%	2%	73%		1%	1%	2%			0%	8%	1%
W	0%	0%	0%	0%	0%		0%			0%	2892%		0%
Va	0%		0%				0%			0%	0%		0%
Zn	9%	7%	10%		58%		12%	23%	2%				4%
Zr	0%	0%	0%				2%	0%			0%		0%
RE	3%	25%	2%	1%		0%	2%			0%		43%	8%

Annex 10 - Material requirements as percentage of regions reserves according to the B2DS

B2DS	World	OECD	Non-OECD	ASEAN	EU	Brazil	China	India	México	Russia	South Africa	USA	Africa +
Al	2%	718%	1%	1%		1%	10%	8%		2%			1%
B	0%	0%	0%				0%			0%		60%	0%
Cd													
Cr	5%	38%	4%					4%			0%	790%	1%
Co	149%	676%	111%	305%							28%	7264%	39%
Cu	12%	8%	15%	28%			70%		4%			31%	6%
Ga													
Ge													
Au	1%	1%	1%	1%		0%	4%		0%	0%	0%		0%
C	30%	23%	35%			4%	30%	128%	43%				70%
In													
Fe	5%	4%	5%		12%	1%	11%	10%			4%	79%	3%
Pb	42%	28%	55%		312%		49%	213%	11%	13%			37%
Li	85%	40%	166%		1713%	847%	87%					6140%	129%
Mg	0%	0%	0%		0%	0%	0%	0%		0%			0%
Mn	9%	18%	7%			1%	24299%	21%	21%		0%		3%
Mo	14%	41%	10%				4%		50%	11%		431%	9%
Ni	88%	104%	81%	85%		10%	361%			30%	9%	8845%	74%
Nb	3%	14%	2%			0%							
Pd	2%	385%	2%							1%	0%	273%	1%
Se	32%	29%	32%		28%		23%			1%		32%	28%
Ag	26%	17%	30%		4%		67%		10%	2%			16%
Ta	12%	7%	23%			0%							
Te	165%	174%	158%		196%		142%					143%	79%
Sn	50%	84%	45%	12%		6%	40%			2%			89%
Ti	3%	2%	4%	150%		2%	3%	4%			0%	15%	3%
W	0%	0%	0%	0%	0%		0%			0%	2885%		0%
Va	0%		0%				0%			0%	0%		1%
Zn	9%	8%	10%		60%		12%	25%	2%				5%
Zr	0%	0%	0%				2%	0%			0%		0%
RE	4%	31%	3%	2%		1%	2%			1%		55%	12%

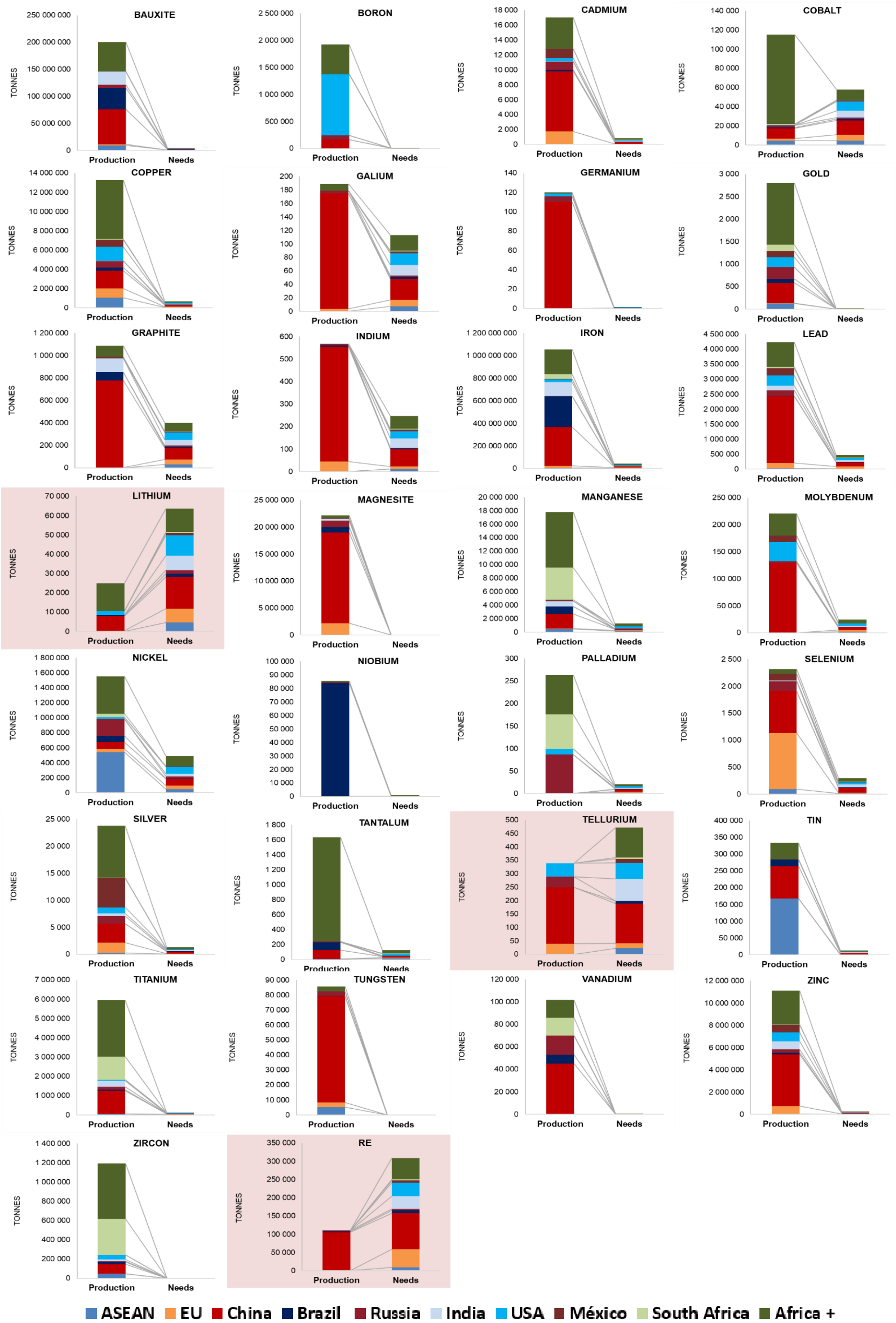
Annex 11 - Distribuiton by regions of hybrid and electric vehicles according to each scenario , until 2060.

		RTS					2DS					B2DS				
	Million Vehicles	2014	2030	2045	2060	Million Vehicles	2014	2030	2045	2060	Million Vehicles	2014	2030	2045	2060	
ASEAN	Hybrids	0.0	1.7	16.6	55.9	Hybrids	0.0	2.7	22.6	35.1	Hybrids	0.0	3.3	21.6	17.3	ASEAN
	PHEV	0.0	0.6	6.4	28.0	PHEV	0.0	1.9	22.4	64.4	PHEV	0.0	2.5	21.2	48.0	
	BEV	0.0	0.3	3.5	16.7	BEV	0.0	1.7	16.8	45.5	BEV	0.0	3.3	50.4	112.3	
BRAZIL	Hybrids	0.3	1.1	6.1	18.1	Hybrids	0.3	1.3	7.8	12.6	Hybrids	0.3	1.9	7.4	6.4	BRAZIL
	PHEV	0.0	0.4	2.4	9.1	PHEV	0.0	0.9	7.8	23.1	PHEV	0.0	1.4	7.3	17.8	
	BEV	0.0	0.2	1.3	5.4	BEV	0.0	0.8	5.8	16.3	BEV	0.0	1.9	17.4	41.6	
CHINA	Hybrids	4.8	47.7	118.7	177.9	Hybrids	4.8	41.1	97.9	103.3	Hybrids	4.8	39.9	70.4	42.8	CHINA
	PHEV	0.2	16.5	45.9	89.2	PHEV	0.2	28.6	96.9	189.4	PHEV	0.2	29.6	69.3	118.7	
	BEV	0.6	8.4	24.7	53.1	BEV	0.6	26.6	72.6	133.9	BEV	0.6	39.8	164.5	277.5	
EU	Hybrids	2.6	16.9	40.9	78.2	Hybrids	2.6	16.5	37.8	38.4	Hybrids	2.6	16.4	28.3	15.8	EU
	PHEV	0.1	5.9	15.8	39.2	PHEV	0.1	11.5	37.4	70.4	PHEV	0.1	12.2	27.8	43.9	
	BEV	0.3	3.0	8.5	23.3	BEV	0.3	10.7	28.0	49.8	BEV	0.3	16.4	66.1	102.6	
INDIA	Hybrids	0.6	7.3	31.6	86.0	Hybrids	0.6	5.7	32.8	54.1	Hybrids	0.6	6.3	29.6	25.7	INDIA
	PHEV	0.0	2.5	12.2	43.1	PHEV	0.0	4.0	32.5	99.2	PHEV	0.0	4.7	29.1	71.3	
	BEV	0.1	1.3	6.6	25.7	BEV	0.1	3.7	24.3	70.1	BEV	0.1	6.3	69.1	166.5	
MEXICO	Hybrids	0.0	0.5	3.9	11.0	Hybrids	0.0	0.7	4.2	5.9	Hybrids	0.0	1.1	4.1	3.3	MEXICO
	PHEV	0.0	0.2	1.5	5.5	PHEV	0.0	0.5	4.1	10.9	PHEV	0.0	0.8	4.0	9.3	
	BEV	0.0	0.1	0.8	3.3	BEV	0.0	0.5	3.1	7.7	BEV	0.0	1.1	9.5	21.7	
RUSSIA	Hybrids	1.8	8.7	16.5	23.5	Hybrids	1.8	5.3	9.8	9.2	Hybrids	1.8	4.9	6.7	4.1	RUSSIA
	PHEV	0.1	3.0	6.4	11.8	PHEV	0.1	3.7	9.7	16.8	PHEV	0.1	3.6	6.6	11.3	
	BEV	0.2	1.5	3.4	7.0	BEV	0.2	3.4	7.2	11.9	BEV	0.2	4.9	15.6	26.3	
SA	Hybrids	0.2	0.9	2.6	5.4	Hybrids	0.1	0.6	2.1	2.9	Hybrids	0.1	0.7	1.8	1.5	SA
	PHEV	0.0	0.3	1.0	2.7	PHEV	0.0	0.4	2.0	5.3	PHEV	0.0	0.5	1.7	4.1	
	BEV	0.0	0.2	0.5	1.6	BEV	0.0	0.4	1.5	3.8	BEV	0.0	0.7	4.1	9.6	
USA	Hybrids	0.4	10.3	55.8	119.6	Hybrids	0.4	26.7	66.9	71.1	Hybrids	0.4	27.6	55.8	33.2	USA
	PHEV	0.0	3.6	21.6	60.0	PHEV	0.0	18.6	66.3	130.3	PHEV	0.0	20.5	54.9	92.3	
	BEV	0.0	1.8	11.6	35.7	BEV	0.0	17.2	49.6	92.1	BEV	0.0	27.5	130.4	215.7	
AFRICA+	Hybrids	0.8	7.5	35.7	132.8	Hybrids	0.8	7.0	43.9	86.5	Hybrids	0.8	9.6	47.4	48.0	AFRICA+
	PHEV	0.0	2.6	13.8	66.6	PHEV	0.0	4.9	43.4	158.6	PHEV	0.0	7.1	46.6	133.3	
	BEV	0.1	1.3	7.4	39.6	BEV	0.1	4.5	32.5	112.1	BEV	0.1	9.6	110.7	311.5	
	Million Vehicles	2014	2030	2045	2060	Million Vehicles	2014	2030	2045	2060	Million Vehicles	2014	2030	2045	2060	

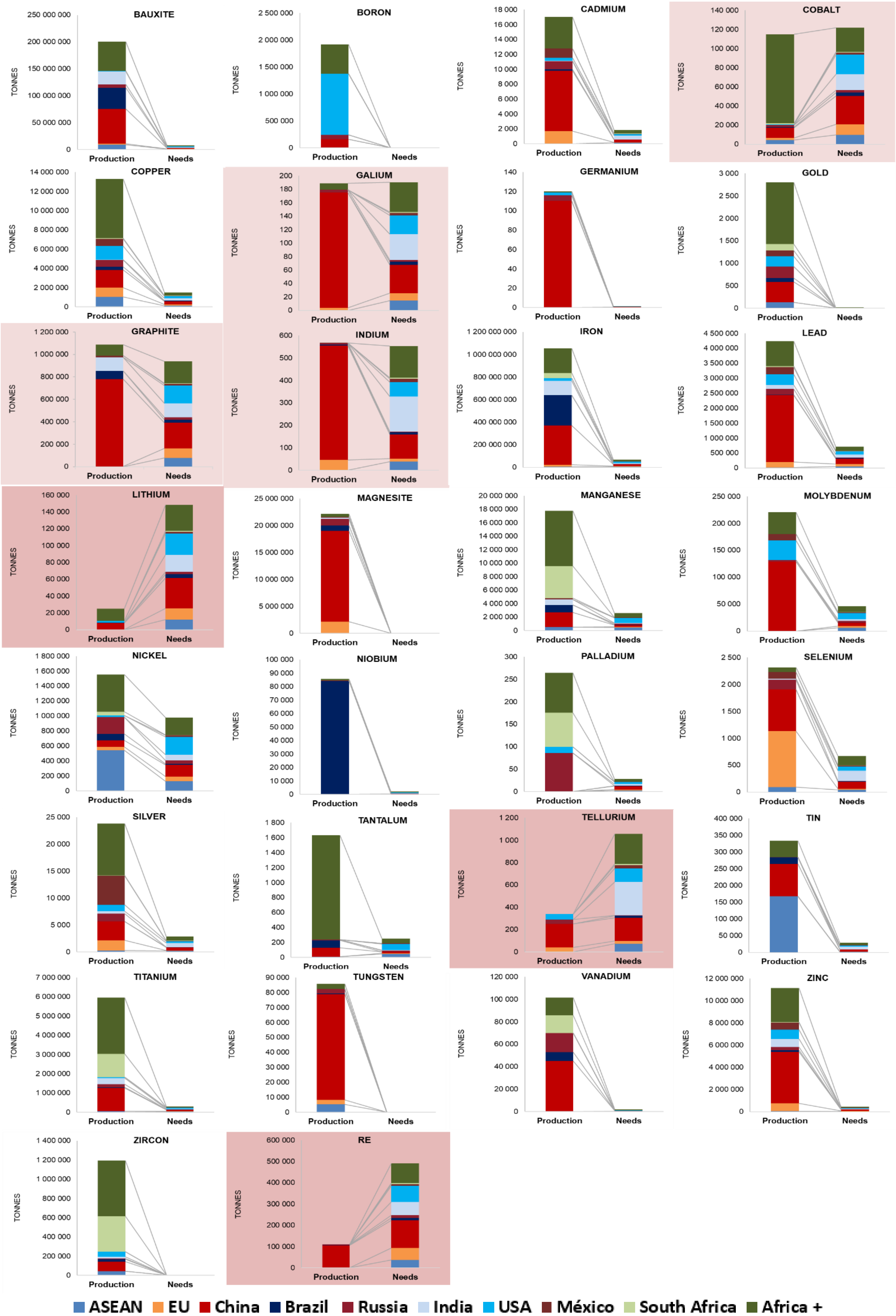
Annex 12 – Mine energy factors used. Retrieved from (Norgate and Haque 2010)

	Stage	Item	Value	Units	% of total
Open Cut (Iron Ore)					
	Drilling	Diesel	0.03	kg/t Ore	**0.9%**
	Blasting	Explosives	0.5	kg/t Ore	
	Loading & Hauling	Diesel	2.2	kg/t Ore	**64.7%**
	Crushing & Screening	Electricity	2.5	kWh/t Ore	**65.8%**
	Stacking & Reclaiming	Electricity	0.5	kWh/t Ore	**13.2%**
	Rail Transport	Diesel	0.5	kg/t Ore	**14.7%**
	Port Operations	Electricity	0.8	kWh/t Ore	**21.1%**
	Overall	Water	0.21	m3/T Ore	
		Diesel	3.4	kg/t Ore	
			135	MJ/T Ore	
		Electricity	3.8	kWh/t Ore	
		Explosives	0.5	kg/t Ore	
		Waste Rock	1.3	T/t Ore	
Open Cut (Bauxite)	Stage	Item	Value	Units	% of total
	Drilling	Diesel	0.03	kg/t Bauxite	**3.2%**
	Blasting	Explosives	0.3	kg/t Bauxite	
	Loading & Hauling	Diesel	0.9	kg/t Bauxite	**96.8%**
		Electricity	0.1		**5.0%**
	Crushing & Blending	Electricity	1.7	kWh/t Bauxite	**85.0%**
	Benefit	Electricity	0.1	kWh/t Bauxite	**5.0%**
	Overall	Water	0.3	m3/T Bauxite	
		Diesel	0.93	kg/t Bauxite	
			38	MJ/T Bauxite	
		Electricity	2	kWh/t Bauxite	
		Explosives	0.3	kg/t Bauxite	
		Waste Rock	0.3	T/T Bauxite	
Underground (Copper)	Stage	Item	Value	Units	% of total
	Drilling	Diesel	0.7	kg/t Ore	**25.0%**
	Blasting	Diesel	0.1	kg/t Ore	**3.6%**
		Explosives	0.4	kg/t Ore	
	Loading & Hauling	Diesel	2	kg/t Ore	**71.4%**
	Ventilation	Electricity	8	kWh/t Ore	**17.2%**
	Dewatering	Electricity	3.8	kWh/t Ore	**8.2%**
	Crushing & Grinding	Electricity	18.5	kWh/t Ore	**39.9%**
	Concentrating	Copper Pray	16.2	T ore/t Concentrate	
		Electricity	7.5	kWh/t Ore	**16.2%**
		Reagents	1.7	kg/t Ore	
		Grinding Media	1.4	kg/t Ore	
		Tailings	37	T/t Concentrate	
	Overall	Copper Pray	16.2	T ore/t Concentrate	
		Water	0.51	m3/T Ore	
		Diesel	2.8	kg/t Ore	
			115	MJ/T Ore	
		Electricity	46.4	kWh/t Ore	
		Explosives	0.4	kg/t Ore	
		Reagents	1.7	T/t Ore	
		Grinding Media	1.4	kg/t Ore	
		Waste Rock	0.03	T/t Ore	
		Tailings	2.3	T/t Ore	

Annex 13 - Regional annual production vs regional average annual needs, according to the RTS.



Annex 14 - Regional annual production vs regional average annual needs, according to the 2DS.



Annex 15 - Regional annual production vs regional average annual needs, according to the B2DS.